HHS Public Access
Author manuscript
IEEE Int Conf Rehabil Robot. Author manuscript; available in PMC 2020 June 01.

Published in final edited form as:
IEEE Int Conf Rehabil Robot. 2019 June ; 2019: 305–310. doi:10.1109/ICORR.2019.8779398.

A Human-assistive Robotic Platform with Quadrupedal Locomotion

Tao Shen,
College of Aeronautics and Engineering in Kent State University, Kent, OH 44242 USA.

Md Rayhan Afsar,
Department of Mechanical Engineering, University of Alabama, Tuscaloosa, AL 35401, USA

Md Rejwanul Haque,
Department of Mechanical Engineering, University of Alabama, Tuscaloosa, AL 35401, USA

Eric McClain [PhD candidate],
Department of Mechanical Engineering, University of Utah, SLC UT 84112, USA

Sanford Meek,
Department of Mechanical Engineering, University of Utah, SLC UT 84112, USA

Xiangrong Shen
Department of Mechanical Engineering, University of Alabama, Tuscaloosa, AL 35401, USA

Abstract

Mobility impairment is becoming a challenging issue around the world with a rapid increase on aging population. Existing tools of walking assistance for mobility-impaired people include passive canes or wheeled rollators which increase energy consumption on the users and disturb the users' walking rhythm, and powered wheeled chairs which could preclude the muscle activities and accelerate the degeneration of the lower limbs. The research in this paper aiming at helping mobility-impaired people proposes a novel robotic platform with quadrupedal locomotion. With motorized actuation, the quadruped robotic platform could accompany the user at the center and provide protection and possible walking assistance if needed. As the robotic platform is equipped with a leg locomotion, it can enlarge the user's activity environments, such as both indoor flat floor and outdoor uneven terrain. It can even assist the user to involve in some mobility challenging activities, such as climbing stairs. In this paper, we illustrate the mechanical design of the robotic platform. A continuous gait planning is proposed to create a smooth locomotion for the robot. To quantify the performance, a system-level walking experimentation was conducted, and the results showed that quadruped robotic platform can maintain a statically stability which demonstrate the feasibility and capability of the robotic application for walking assistance.

Corresponding author, 205-348-6743, xshen@eng.ua.edu.

I. Introduction

Aging of the population is a major health challenge that affects many countries in the world. In the United States, the number of individuals aged 65 and older is expected to double between 2007 and 2032, and there will be 71 million older adults, accounting for 20% of the U.S. population by 2030 [1]. For the health and wellbeing of older adults, a key contributing factor is to be physically active. Research shows that regular physical exercise is highly effective in the prevention of cardiovascular and neurodegenerative diseases, stroke and diabetes [2, 3], as well as the improvement of balance control and functional performance [4, 5] for older adults. Despite the obvious benefits of regular physical exercise, many older adults lack adequate mobility needed for a physically active life style, and the specific challenges include the lack of physical strength and high risk of fall [6].

To help mobility-challenged individuals to overcome such barriers, a variety of assistive tools have been developed and utilized. Among them, mobility aids and wheelchairs (powered and unpowered) are the most extensively used types in the current practice. Mobility aids are unpowered devices that assist older adults in maintaining their balance and reducing their lower-limb loads in walking [7, 8]. They are simple, lightweight, and easy to transport. However, their problems are also obvious. Without power, a mobility aid requires the user to lift and advance the device for each step, which not only increases energy expenditure, but also places heavy cognitive burden on the user [9]. Unlike walking aids, wheelchairs allow users to take a seated position when moving about, which minimizes the risk of falls. Powered wheelchairs also minimizes the user's metabolic energy consumption in the movement. However, a wheelchair largely precludes lower-limb muscle activity and bone load carrying, and thus accelerates the musculoskeletal degeneration [10].

In recent years, with the rapid technological advances in actuation and control technologies, researchers have explored various approaches to enhance the performances of walkers and wheelchairs. For example, the PAM-AID walker is equipped with a rotatable handle to allow the user to control the walking direction easily, and it also has an assistive mode with automatic steering to avoid obstacles [11–13]; the PAMM walker monitors the user's health (through approaches such as ECG measurement) and reminds the user about scheduled tasks [14]. Despite these additions of such novel features, a common problem that affects almost all existing assistive devices still exists: their inability to overcome obstacles. In the real-world application of an assistive device, it is very common for the mobility-impaired user to face various types of small obstacles: the roadside curbs, a few stairs at the front door of a house, etc. As existing devices are largely designed for level-ground (or slightly sloped ground) applications, users of such devices may face significant challenges in manipulating the assistive devices to overcome even the smallest obstacles, given the low physical strength of these users.

Motivated by such observation, the authors propose a fundamentally different approach in the development of new mobility-assist devices. Instead of using the ubiquitous wheeled locomotion, the assistive robot in this paper utilizes legged locomotion, leveraging its superior capability in overcoming challenging terrains. Fig. 1 shows the concept of the Quadrupedal Human-Assistive Robotic Platform (Q-HARP) when it is assisting a human user in walking. As depicted in this figure, the Q-HARP robot is essentially a smart and powered walker with two robotic legs on each side, with the desired functions of enhancing the user stability and supporting the user in walking. With the legged locomotion, the Q-HARP would be able to easily overcome the common obstacles in the user's daily life, with minimal efforts expended by the user. As the basis of this novel assistive robot, the research presented in this paper includes the design of the robotic platform, the legged walking controller with the enhanced stability, and the preliminary results of robot testing. Such results are anticipated to lay a foundation for the subsequent human-robot interaction study to achieve the desired Q-HARP functionality.

II. Design of the Q-HARP

The Q-HARP is a special type of assistive robot that walks alongside the user and provides assistance and protection in the process. As such, the robotic legs are expected to provide comparable performance as human legs, including the configuration, torque capacities, and kinematic performances. The ultimate goal for this project is to design a smart quadruped robotic walker guided by an image processing system. As the image processing system has been verified with a wheeled robot in [15], this paper focuses on the quadruped robotic walker design and control. For the simplicity of the robot system, each robotic leg only incorporates two active rotational joints, emulating the functions of the hip and knee. A passive ankle joint with a flat foot is attached on each leg to provide support and angle compensation, which can keep a full flat foot, ground touch. The front two legs have the knee backward facing as shown in Figure 1, thus the four legs are configured like two pairs of human legs facing each other. This configuration could make the robot compact as all the legs are bent into the center of the robot. Furthermore, due to the large number of joints in the system, the authors selected the powered prosthetic knee joints developed in the related robotic prosthesis research [16], significantly reducing the cost and risk in the development of the Q-HARP. As such, the design of the Q-HARP was focused on the hip joints, with the details presented as follows.

A. Powered Hip Joint Design

The hip joint expends significant amount of torque and power in the locomotion of the quadruped robot, as it serves important functions in both swing and stance phases. During swing, the hip carries the weight of the entire robotic leg while rapidly reconfiguring the leg for the subsequent ground contract. During stance, the hip is the major power source for the robot's forward movement, since the simple two-degree-of-freedom leg does not include a powered ankle joint (the ankle is the major source of power in human locomotion [17]), and the power contribution from the knee joint is minimal. As such, the primary design goal of the robotic hip joint in this work is maximize the torque capacity while still providing sufficient joint velocity to facilitate the swing motion.

Unlike the preliminary work conducted on a pneumatically-actuated quadruped robot [18], the Q-HARP is powered with DC motor-based actuation approaches for the convenience in control and testing, as well as the greater potential of developing into practical devices in the future. However, DC motor is a typical type of high-speed and low-torque actuator, usually requiring a high-gear-ratio transmission to boost its torque output to power robotic joints. Such transmission systems tend to be heavy, bulky, and expensive, diminishing the practicality of the robot in real-world application. To address this problem, the design of the hip actuation system was conducted based on a high-current, low-speed DC motor (U8-10, T-Motor, Jiangxi, China), a type of motor commonly used in unmanned aerial vehicles. While the speed of the motor is relatively low, it is still too high for direct actuation. The high torque capacity of this motor, as a result of its high current capacity, makes it possible to use a low transmission ratio to obtain the desired output torque. As a result, the transmission can be made much smaller and simpler, significantly improving the practicality of the robot system.

The overall design of the hip actuation system is shown in the schematic in Fig. 2. A two-stage miniature chain drive was utilized for gear reduction. Compared with the traditional gear set, the chain drive provides greater flexibility in the arrangement of system components. Furthermore, the compliance in this flexible transmission approach helps to buffer the impact loading resulting from the robotic leg's ground contact, making the operation smoother. On the other hand, a chain drive's smooth operation requires the chain to be properly tensioned, and thus the system tends to be more complex due to the use of related adjustment mechanisms (using a chain tensioner or making the sprocket distance adjustable). Such challenge is more significant for the two-stage chain drive in the Q-HARP, considering the limited space available.

To maintain the compactness of the system, the design in the Q-HARP incorporates a unique linear adjustment mechanism, as shown in Fig. 2b. The intermediate shaft, which connects the output sprocket of the 1st-stage and the input sprocket of the 2nd-stage, is placed on a slider that moves in the transverse direction. When the slider moves away from the center, the sprocket center-to-center distance increases for both stages. As a result, such linear adjustment enables the chains to be tensioned simultaneously, significantly simplifying the system design. In the design of the adjustment mechanism, calculation was conducted to ensure that both stages can be tensioned correctly when the slider reaches the desired location. Mechanically, the apparatus for such adjustment is also minimal, only requiring a threaded pushrod to push the slider when turning in the correct direction. Note that, after the desired tensions are obtained, the slider is fastened to the frame through four button-head screws, and thus the pushrod can be removed to maintain the smoothness of the actuator profile.

As shown in Fig. 2a, the components of the hip actuation system are all housed in the horizontal U-shaped frame to simplify the wiring connection. With the use of the rotational system, the output range of motion is essentially unlimited. To facilitate the experimental tuning of the controller, shoulder-bolt-based bumpers were installed to limit the joint movement and minimize the possible damage when a controller malfunctions. The design parameters of the actuation system are summarized as follows: the motor shaft is directly coupled to a 7-teeth small sprocket, which drives a 54-teeth sprocket supported by the aforementioned intermediate shaft through a RS15 roller chain; on the same shaft, the motion is transmitted to a 7-teeth double sprocket, which drives a 45-teeth double sprocket through two parallel RS25 roller chains. Such two-stage design provides a total transmission ratio of almost 50:1, and thus the output joint torque reaches as high as113 N-m. Such high torque capacity forms a basis for the implementation of the stable walking control algorithm, and the performance was demonstrated in the walking experiments in Section IV.

B. Powered Knee Joint and Prosthetic Components-Constructed Robotic Leg

As mentioned above, the knee joints in the Q-HARP are essentially the powered prosthetic knee joints developed in the authors' robotic prosthesis research [16]. For the completeness of presentation, the design and performance of the powered knee joints are summarized below.

The prosthetic knee, as shown in Fig. 3, is powered by an 8-pole brushless DC motor rated at 70 W (EC 45 flat, Maxon Motor, Sachseln, Switzerland). This motor is able to generate a peak torque of 200 mNm for short-term operation. To boost its torque output, a two-stage transmission is developed to provide a combined ratio of 150:1. The first stage is a timing belt drive with a ratio of 1.5:1, and its primary function is to decouple the motor from the major gear-reduction device (harmonic drive in the second stage), providing the flexibility in the arrangement of system components. The second stage is a harmonic drive with a 100:1 gear ratio (SHD-20-100-2SH, Harmonic Drive, Peabody, MA). The harmonic drive was selected as it provides a large gear ratio within a compact package. Additionally, a cross-roller bearing is incorporated into its structure, allowing the output shaft to be directly mounted without additionally bearing support. After such two-stage gear reduction, the output torque can reach as high as 30 Nm. Note that, in the prosthesis design, reducing the weight and simplifying the system structure was given higher priority than generating higher torque output. The resulted knee prosthesis, nonetheless, provides sufficient torque for a 75kg person in his/her slow walking.

After constructing the two powered joints, each robotic leg was assembled with the standard prosthetic connection techniques. The purpose is to leverage the rich choices of prosthetic components to provide high flexibility in connection and adjustment. An output adapter was designed and fabricated to mount a standard prosthetic tube connector to the hip joint. Standard prosthetic tubes are used to connect hip joints to the corresponding knee joints. For the robotic foot for each leg, both standard prosthetic stomper (a rubber multi-sectional circular piece) and standard prosthetic foot (covered by a rubber foot shell and then inserted into a shoe) have been tested. Fig. 4 shows the complete Q-HARP system after it was fully assembled, and Fig. 4b shows the details of a robotic leg. Note that, due to budgetary limitation, only two custom hip joints (two rear legs) were fabricated and fitted to the Q-HARP. The other hip joints (two front legs) are currently powered with the off-the-shelf harmonic actuators (FHA-17C-E, Harmonic Drive, Peabody, MA), which are expected to be replaced by the custom hip actuators in the future. The leg thigh is 0.394 m; the shank is 0.343 m; and the distance between the ankle joint and the foot bottom is 0.14 m. This length design is mimicking human legs design with the principle in [19]. The hips of the four legs are attached with the top three U-shape aluminum frames, in which two frames are set on two sides and one is in the front. The robot has 0.46 m width and 0.635 m length.

III. Gait planning and Control

Coordinating the movement of multiple legs is one of the biggest challenges in quadruped robots [20]. The gaiting planning involves the leg sequence planning and the leg joint trajectory generating, and the purpose is to maintain a stable walking. Current researches are focused on two type of stability including static stability and dynamic stability [21]. The static stability is usually a major consideration in slow moving quadruped robots, while dynamic stability is a key concern in a quadruped robot with a high walking speed. After the leg sequence planning, the leg joint trajectory generating is a following step to create the motion for each joint. Current research in joint trajectory generation is based on inverse kinematics with DH convention [22]. Nonetheless, with only this classic convention, the smoothness of the trajectories has a big compromise. In this section, we follow a fundamental quadruped gait theory to plan the leg sequence to maintain a static stability for the robot. We also propose a continuous joint trajectory planning method with a spline interpolation, which maintains continuity not only in positon, but also in velocity and acceleration.

A. Leg Sequence

As this robot is supposed to provide walking assistance for senior people or other mobility-impaired persons, the walking velocity is expected to be slower than normal people's walking speed. Thus, with this concern, the priority of the robot development is to keep the quadruped robot always in a static stability during which the center of mass (COM) should be always within the support polygon.

Some symbols are need to be defined: E is the leg stroke length which is a distance that a foot is moved relative to the robot body during the stance phase of this leg; β is the duty factor of a leg which is the fraction of the cycle when the leg is on the ground; λ is the stride length which is the distance traveled by the COM during a total cycle. The relationship between β, E and λ is as shown in Eq. (1). The definition is based on quadruped locomotion convention in [23].

$$\beta = \frac{E}{\lambda} \tag{1}$$

According to [24], the duty factor of the leg should be within the range of (0.75, 1) so that it can guarantee a positive stable margin S in the moving direction to make the COM always be within the support polygon.

The gait pattern used in this paper is a typical lateral sequence [20], in which the feet swing in the order as Front Left (FL), Rear Right (RR), Front Right (FR), and Rear Left (RL). Here we number the legs as FL (Leg 1), RL (leg 2), FR (Leg 3), and RR (Leg 4).

If the robotic body is moving in a constant speed with T as the leg cycling period and the gait follows the proposed gait patterns, the phase of the legs can be shown as Fig. 5.

As shown in Fig. 5, the dark solid lines denote the stance phase for the legs, and the rest is swing phase. The front legs (Leg 1 and Leg 3) are ½ T out of phase from each other; the rear legs (Leg 2 and Leg 4) are ½ T out of phase from each other; each front leg leads the rear on the same side by βT, where T is the leg period.

To ensure the robot can remain stable with disturbances from a human user, a proper value for β should be selected. A method has been proposed in [25] to determine a value for the gait that provides stability to the system when disturbed and minimizes the overall energy consumption of the robot. With this method a value of $\beta = 0.81$ was found for this system.

B. Joint trajectory generator

Trajectory planning of manipulators has been thoroughly explored in robotics and is covered in many texts. To obtain a smooth operation of a robot manipulator, it is desired to maintain continuity in the position, velocity and acceleration of the desired path. To achieve this goal, polynomial splines can be used to generate the trajectories. The method to the trajectory for one of the legs of the robot is described in details in this section.

For a 2-DOF leg, the trajectory planning was performed as follows. The trajectory in the stance phase, from time t_0 to t_1, is a line of the position through time with constant velocity v and step length E as follows

$$\begin{aligned} x(t) &= \frac{E}{2} - vt \\ y(t) &= 0 \end{aligned} \tag{2}$$

where x is the distance from the hip in the forward direction, y is the distance that the foot is lifted above the ground. The trajectory for the swing phase, from time t_1 to t_f, begins at the final position of the stance phase, lifts to a height h_{lift}, then ends at the initial position of the following swing phase to complete the cycle. To ensure a smooth trajectory, the stance and swing trajectories mesh in position and velocity. With these constraints, a cubic spline can be used to define the trajectory in x as

$$x(\tau) = \frac{-E}{2} - v\tau + \frac{3E + 3vt_s}{t_s^2}\tau^2 - \frac{2E - 2vt_s}{t_s^3}\tau^3 \tag{3}$$

where $\tau = t - t_1$ and t_s is the duration of the swing phase($t_s = t_f - t_1$). The position in y can be split into two sections with each section defined using 2 cubic splines

$$y(\tau) = \begin{cases} \dfrac{3h_{lift}}{(t_s/2)^2}\tau^2 - \dfrac{2h_{lift}}{(t_s/2)^3}\tau^3, & \text{if } \tau \le \dfrac{t_s}{2} \\ h_{lift} - \dfrac{3h_{lift}}{(t_s/2)^2}(\tau - t_s/2)^2 + \dfrac{2h_{lift}}{(t_s/2)^3}(\tau - t_s/2)^3, & \text{if } \tau > \dfrac{t_s}{2} \end{cases} \tag{4}$$

Using these equations, the foot trajectory can be solved for through the entire gait cycle using the following parameters.

$$\begin{aligned}&(\text{stride length})\ \lambda = E/\beta\\&(\text{frequency})\ f = v/\lambda\\&(\text{period})\ T = 1/f = \lambda/v\\&t_0 = 0\\&t_1 = \beta T\\&t_s = (1-\beta)T\\&t_f = T\end{aligned} \tag{5}$$

Fig. 6 shows sample trajectories generated for $E = 0.272$ m, $h_{lift} = 0.15\ m$ and $\beta = 0.81$. t_0, t_1 and t_2 are shown on the top trajectory for clarity.

Implementing control of joint angles requires the desired joint angles. After solving the foot trajectory in operation space we can solve for the joint angles using inverse kinematics. For a planar manipulator this can be done using (6)–(9) which are obtained through the geometric relationships in Fig. 7.

$$\theta_2 = \pm 2tan^{-1}\left(\sqrt{\frac{\left(l_{th}+l_{sh}\right)^2-\left(x^2+\left(y-h_d\right)^2\right)}{\left(x^2+\left(y-h_d\right)^2\right)-\left(l_{th}-l_{sh}\right)^2}}\right) \tag{6}$$

where x and y are from the foot (ankle shaft) trajectory, h_d is the desired height of the robot body above the ground without considering the passive ankle joint, l_{th} and l_{sh} are the lengths of the thigh and the shank of the leg and θ_2 is the knee angle. The sign of θ_2 is selected to determine the knee forward or knee back configuration as the front and back legs have different configurations.

$$\phi = atan2\left(x, \left(y-h_d\right)\right) \tag{7}$$

$$\psi = atan2\left(l_{th}sin\theta_2, l_{th}+l_{sh}cos\theta_2\right) \tag{8}$$

using ϕ and ψ we can solve for the hip angle θ_1 as

$$\theta_1 = \phi - \psi \tag{9}$$

All the angles of hip and knee joints of the quadruped robot legs can be obtained with this inverse kinematics.

Using the inverse kinematics described above the angles of the joints can be solved in real time. The joint angles of an example of a stable gait ($h_d = 0.711\ m$, $h_{lift} = 0.15\ m$, $l_{th} = 0.394\ m$, $h_{th} = 0.343\ m$, $\beta = 0.81$, $E = 0.272m$, $v = 0.043\ m/s$) are as shown in Fig. 8.

IV. Experiments and Results

To verify the walking functionality and correctness of designed gait, a walking experiment was conducted. Each of the powered joint was controlled by a dsPIC33 microcontroller to do a position control, and the microcontrollers are synchronized with each other through a CAN bus communication.

The robot was held up before the test. After it walked in the air with a stable gait ($h_d = 0.711$ m, $h_{lift} = 0.15$ m, $\beta = 0.81$, $E = 0.272m$, $v = 0.043$ m/s), it was slowly left on the ground for walking test. The expected joint trajectories were generated, and the actual joint rotational positions were recorded for evaluation as shown in Fig. 9. A video is attached to show its actual stable walking performance.

As shown in Fig. 9, the robot can generate constant cycling trajectories. In each joint, the motor can drive the joint to follow the generated trajectories with minor error. The errors of the joint angels in stance phase are a little higher than the swing phase (the swing phase is around the peaks in the figure) since robotic weight is loaded on the foot during the stance phase. Nevertheless, the errors are still in a small and reasonable range. In the video, the robot can walk forward stably.

V. Conclusion

This paper proposes a novel robotic platform with a quadrupedal locomotion which aims to accompany the user and provide walking assistance if needed. With legged mobility, the platform is supposed to expand mobility-impaired users to involve in both indoor and outdoor environments. The legs are actuated with active power, which could reduce the users' metabolic energy consumption. The design of the motorized legs and the structure of the robotic platform was illustrated in this paper. A novel gaiting planning method is proposed to generate continuous and smooth joint trajectory for each joint. A system-level walking experimentation showed the robot could perform a stable walking gait which demonstrates the feasibility and effectiveness of the robotic method. Future work includes optimizing the structure of the robot, organizing the electric wires, improving the automation and conducting clinic experiments.

Acknowledgments

The study is supported by the National Institutes of Health under Grant #R01 NR016151.

References

[1]. Center for Disease Control and Prevention and The Merck Company Foundation (2007) The State of Aging and Health in America 2007 Whitehouse Station, NJ: The Merck Company Foundation.

[2]. Goodwin VA, Richards SH, Taylor RS, Taylor AH, Campbell JL, "The effectiveness of exercise interventions for people with Parkinson's disease: A systematic review and meta-analysis," Movement disorders, vol. 23, no. 5, pp. 631–640, 2008. [PubMed: 18181210]

[3]. Michael KM, Shaughnessy M, "Stroke prevention and management in older adults," Journal of Cardiovascular Nursing, vol. 21, no.5, pp.S21–S26, 2006. [PubMed: 16966926]

[4]. Buatois S, Gauchard GC, Aubry C, Benetos A, Perrin P, "Current physical activity improves balance control during sensory conflicting conditions in older adults," International journal of sports medicine, vol 28, no. 1, pp. 53–58, 2007. [PubMed: 16739089]

[5]. Cress ME, Buchner DM, Questad KA, Esselman PC, Schwartz RS, "Exercise: effects on physical functional performance in independent older adults," The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, vol. 54, no. 5, pp. M242–M248, 1999.

[6]. Schutzer KA, Graves BS, “Barriers and motivations to exercise in older adults,” Preventive medicine, vol. 39, no. 5, pp. 1056–1061, 2004. [PubMed: 15475041]

[7]. LaPlante MP, “Assistive technology devices and home accessibility features: prevalence, payment, need, and trends,” Advance data from vital and health statistics, vol. 16, no. 217, pp. 1–11, 1992.

[8]. Bateni H, Maki BE, “Assistive devices for balance and mobility: benefits, demands, and adverse consequences,” Archives of physical medicine and rehabilitation, vol. 86, no. 1, pp. 134–145, 2005. [PubMed: 15641004]

[9]. Wright DL, Kemp TL, “The dual-task methodology and assessing the attentional demands of ambulation with walking devices,” Physical Therapy, vol. 72, no. 4, pp.306–312, 1992. [PubMed: 1584862]

[10]. Lee B, Ko C, Ko J, Kim JS, Lim D, “Suggestion of new concept for mobility assistive system based on wheelchair platform with gait assistive function controlled by artificial pneumatic muscle,” Biomedical Engineering Letters, vol. 5, no. 2, pp. 87–91, 2015.

[11]. Lacey G, Mac Namara S, Dawson-Howe KM, “Personal adaptive mobility aid for the infirm and elderly blind,” In Assistive Technology and Artificial Intelligence, Springer Berlin Heidelberg, 1998, pp. 211–220.

[12]. Mac Namara S, Lacey G, “A smart walker for the frail visually impaired,” Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065), San Francisco, CA, USA, 2000, pp. 1354–1359 vol.2. doi: 10.1109/ROBOT.2000.844786

[13]. Lacey G, Mac Namara S, “User involvement in the design and evaluation of a smart mobility aid,” Journal of rehabilitation research and development, vol. 37, no. 6, pp. 709–723, 2000. [PubMed: 11321007]

[14]. Dubowsky S, Genot F, Godding S, Kozono H, Skwersky A, Yu H, Yu LS, “PAMM - a robotic aid to the elderly for mobility assistance and monitoring: a “helping-hand” for the elderly,” Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065), San Francisco, CA, USA, 2000, pp. 570–576 vol.1. doi: 10.1109/ROBOT.2000.844114

[15]. Shen T, Afsar MR, Zhang H, Ye C, “Development of a Motorized Robotic Walker Guided by an Image Processing System for Human Walking Assistance and Rehabilitation,” Proceedings of ASME 2018 Dynamic Systems and Control Conference, Atlant, Georgia, USA, pp. V001T07A009; 7 pages, 2018. doi:10.1115/DSCC2018-9223.

[16]. Wu M, Haque MR, Shen X, “Obtaining Natural Sit-to-Stand Motion with a Biomimetic Controller for Powered Knee Prostheses,” Journal of Healthcare Engineering, vol. 2017 (6 pages), 2017 10.1155/2017/3850351

[17]. Farris DJ, Sawicki GS, “The mechanics and energetics of human walking and running: a joint level perspective” Journal of the Royal Society Interface, vol. 9, no. 66, pp 110–118, 2012

[18]. Heim I, Zheng H, Shen X, “A quadruped robot powered with pneumatic actuators.” Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition, pp. IMECE2015–51004, 2015.

[19]. Bartel DL, Davy DT, Keaveny TM, Orthopaedic Biomechanics: Mechanics and Design in Musculoskeletal Systems. 1st ed, Pearson, 2006.

[20]. Owaki D, Kano T, Nagasawa K, Tero A, Ishiguro A, “Simple Robot Suggests Physical Interlimb Communication is Essential for Quadruped Walking,” Journal of The Royal Society Interface, vol. 10, no. 78, 20120669, 2013.

[21]. Santos CP, Matos V, “Gait transition and modulation in a quadruped robot: a brainstem-like modulation approach,” Robotics and Autonomous Systems, vol. 59, pp. 620–634, 2011.

[22]. Zeng Y, Li J, Yang SX, Ren E, “A bio-inspired control strategy for Locomotion of a quadruped robot,” Applied Sciences, vol. 8, pp. 1–18, 2018.

[23]. Santos PGD, Garcia E, Estremera J, Quadrupedal Locomotion-An Introduction to the Control of Four-Legged Robots, Springer-Verlag London, 2006, pp. 58–64.

[24]. Lee T, Shin C, “A Study of the Gait Control of a Quadruped Walking Vehicle,” IEEE Journal of Robotics and Automation, vol. 2, no. 2, pp. 61–69. 1986.

Author Manuscript
Author Manuscript
Author Manuscript

[25]. McClain EW and Meek S, "Determining Optimal Gait Parameters for a Statically Stable Walking Human Assistive Quadruped Robot," in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, 2018.

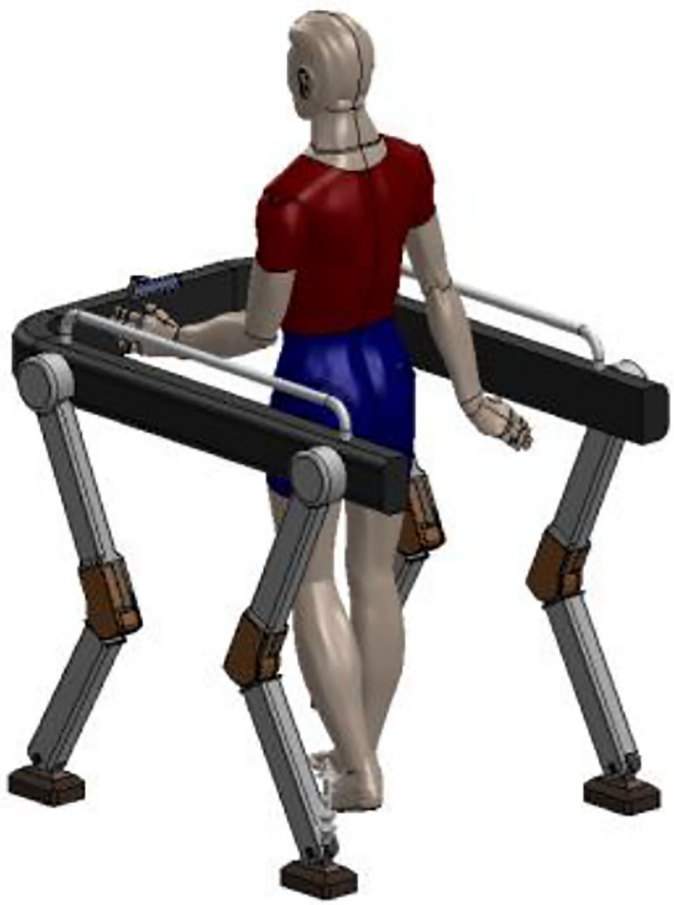


Figure 1.
Concept of the Q-HARP quadrupedal walker.

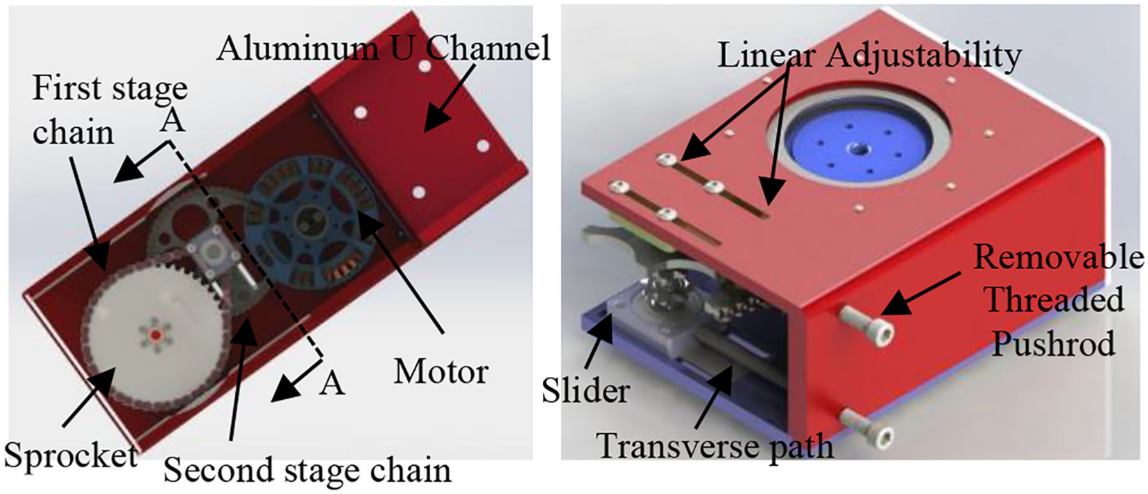


Figure 2.
Design of the hip actuation system: (a) overall view of the actuation system; (b) A-A veiw for the linear adjustment mechanism.

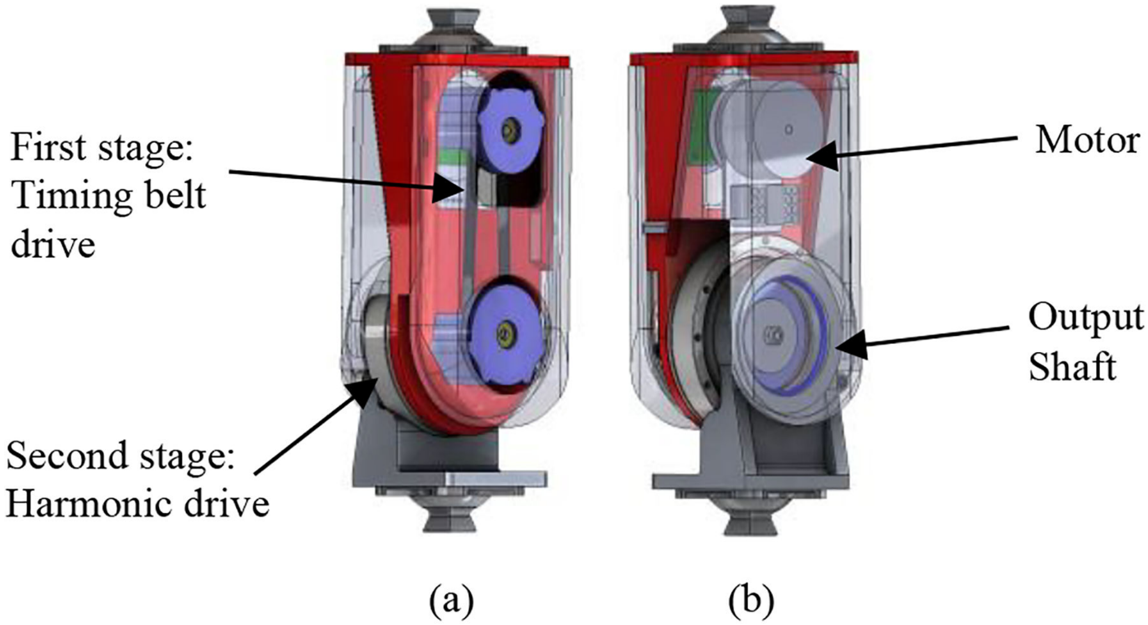


Figure 3.
Actuation system for the knee joint: (a) Transmission-side view (b) Motor-side view.

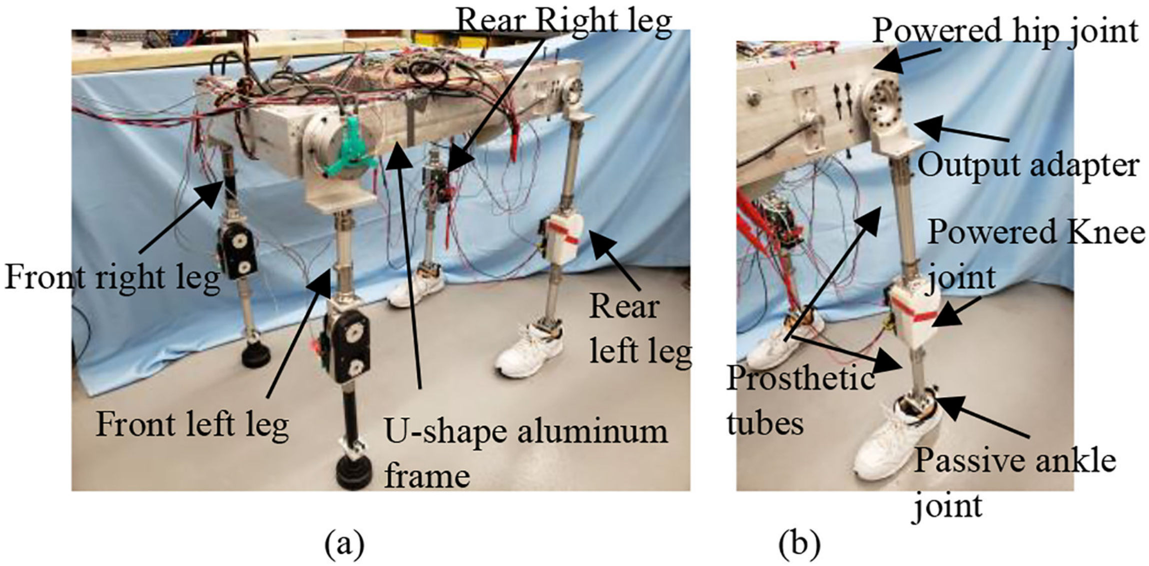


Figure 4.

The assembled Q-HARP prototype: (a) the robot system; and (b) a robotic leg in the Q-HARP.

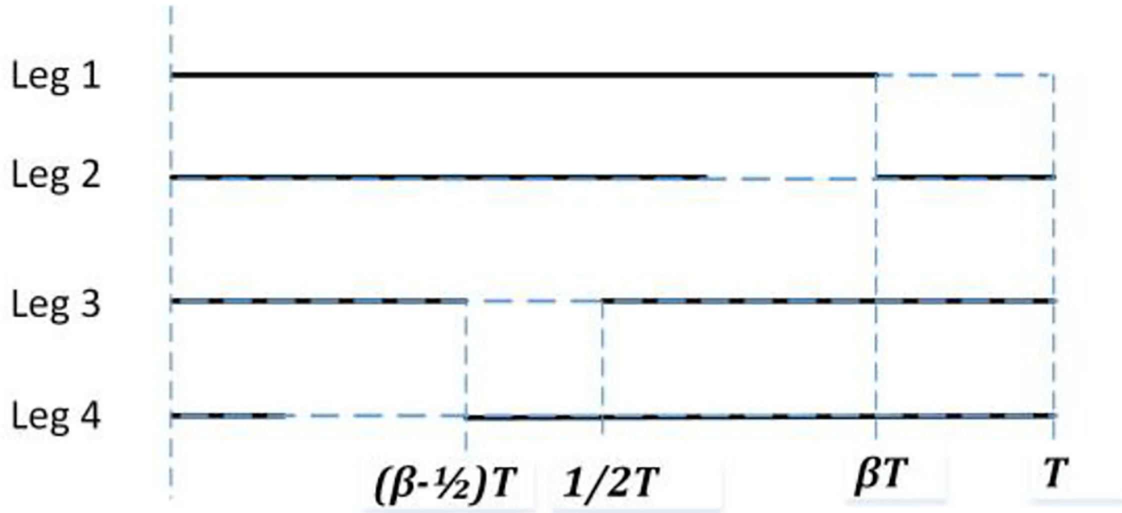


Figure 5.
Leg phase

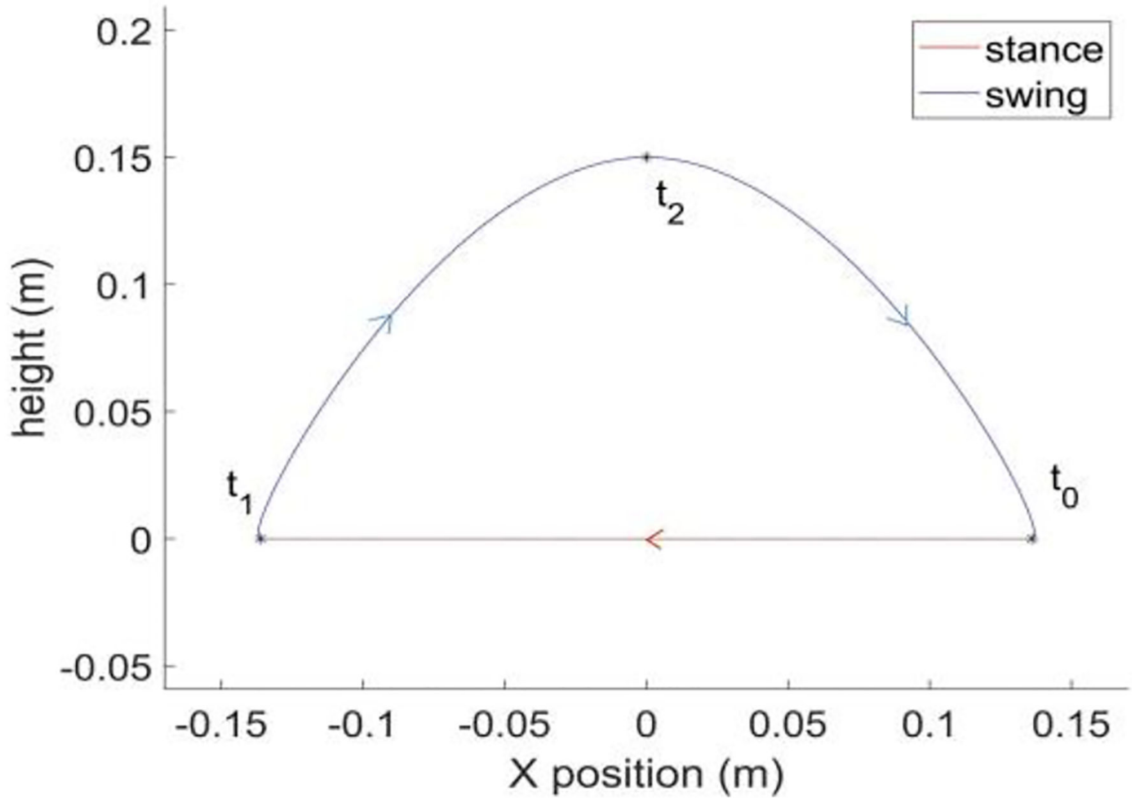


Figure 6.
Example of the foot trajectory generated using (2),(3) and (4).

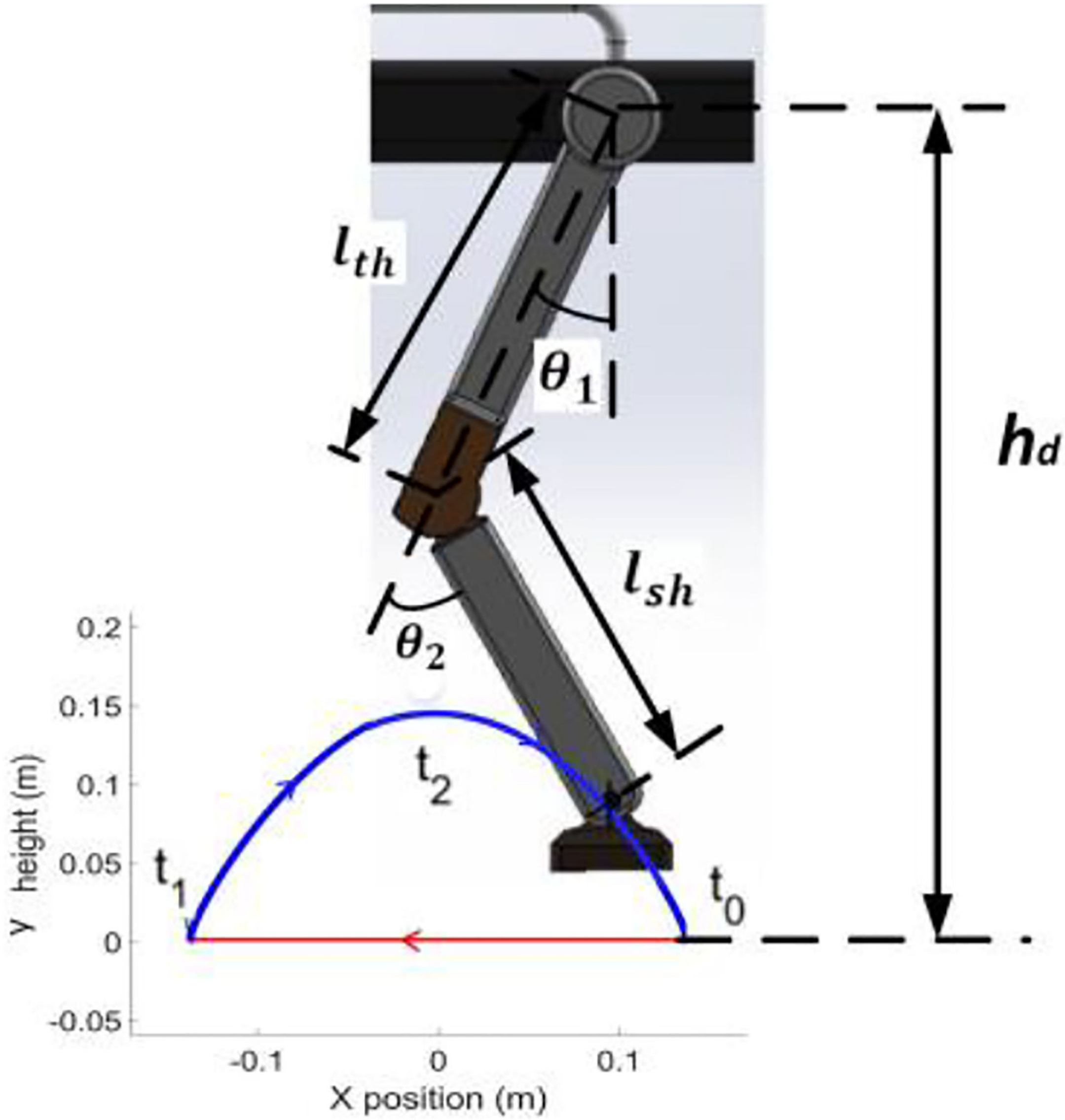


Figure 7.
Geometric relationship for joint trajectory

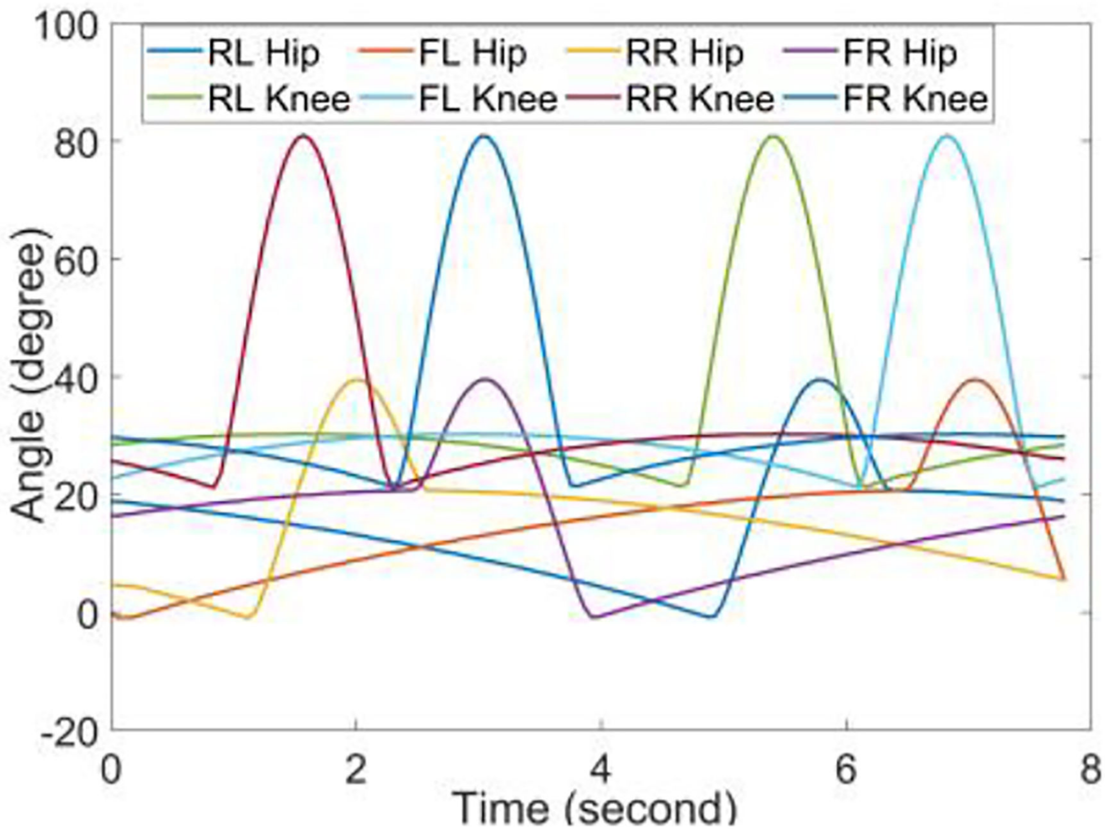
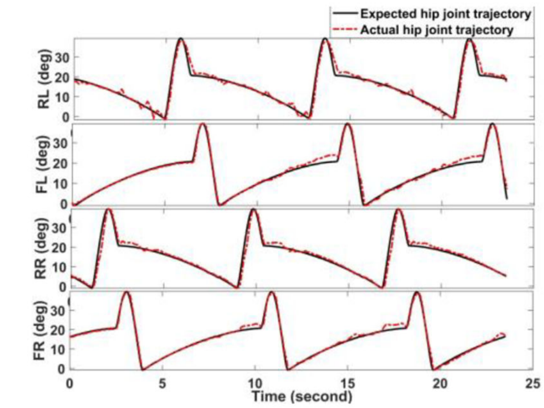
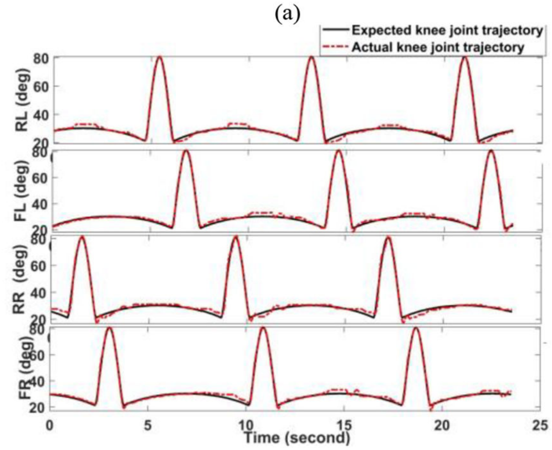


Figure 8.
Joint angle trajectories of an example gait



(a)



(b)

Figure 9.

Positon tracking for the joint trajectory for a stable walking