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Analysis on the Control Strategies of Hip Exoskeletons and Exosuits

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Abstract. Lower limb exoskeleton has been proven to be effective in gait training and locomotion assistance. Specifically, control strategies of exoskeletons play the most important role in safe and effective interaction between the user, the exoskeleton, and the environment. In this paper, an analysis on the control strategies of hip exoskeletons and exosuits is performed. The controls are divided into three levels: high, medium, and low. The definition of high-level control as well as the corresponding control methods are listed and the principle of each is explained. Then, the mid-level control section is divided between detection and action layer and each control that belongs to one of the two categories is analyzed. The definition of low-level control and its control methods are then explained. At last, according to the results of various studies, the advantages and potential disadvantages of each method are put forward. The purpose of this paper is to provide reference and guidance for future researchers who hope to develop new controls or improve existing control strategies for hip exoskeletons and exosuits.

Keywords: analysis, control, exoskeleton, exosuit, hip

1. Introduction

Exoskeletons and exosuits are rehabilitation devices that can facilitate the user's locomotion. They not only achieve safer and lower energy cost of walking for elderlies, but also provide assistance and gait training for patients with neurological impairments. The ability to walk can significantly lower chronic diseases rates and improve mental health for patients and elderlies, thus improving public health in general [1]. Hip exoskeletons and exosuits are two examples among various categories of lower limb orthoses. They provide force and torque assistance at the user's hip joint to assist locomotion. Compared with other joints, the gluteal extensor consumes more energy [2], and assisting the gluteal movement can greatly reduce the net metabolic cost of walking.

Hip exoskeletons are made from rigid components such as lightweight alloy and carbon fiber [3]. Brushless motors [4], pneumatic actuators [5], series elastic actuators [6] as well as other actuation units are used on exoskeletons. Their rigid frames have the advantage of transmitting a large amount of force quickly and accurately. This makes them suitable for patients who suffer from severe loss of muscle strength, hemiplegia, or paraplegia. In contrast, hip exosuits are usually made from fabric that the user can wear around the thigh and waist, using off-board actuation systems or on-board actuation units. For off-board actuation, assistance force is achieved by using Bowden cables that can transfer force across a certain distance [7]. Flexibility of the exosuit can give the user more degrees of freedom

(DOF) during motion and is more comfortable to wear by using textile materials for support. It is most suitable for those who have no difficulty in exercising or can perform enough independent exercise.

Control strategies play the most important role in forming accurate and continuous interactions between the user, the exoskeleton, and the environment. They need to recognize the intention of the user, determine the correct assistance profile, and deliver appropriate force assistance while compensating for various disturbances. To the best of the author's knowledge, few articles have been found to systematically analyze the control strategies of hip exoskeletons or exosuits. Literature [8,9] gives a comprehensive overview of the control strategies, but the scope of both articles covers a variety of types of lower limb exoskeletons, which is not suitable as a reference for the control of hip exoskeletons and exosuits. Chen et al. [10] reviewed the exoskeleton of hip joint but paid less attention to various control strategies and gave a limited explanation for the review of each control.

Relevant publications were found using keyword searches such as "hip", "exoskeleton", "exosuit", "orthosis", "control" in Google Scholar and Samuel C. Williams Library website, articles published time ranging from January 2000 to December 2021. The title and abstract of selected articles were reviewed for their relevance on the topic. Then, articles that were closely related to the subject and had no conceptual overlap with other articles were deeply analyzed.

This article aims to conduct an analysis on the control strategies of exoskeletons and exosuits based on their unique properties to improve rehabilitation effects and assist locomotion in real-world scenarios. The following research hopes to illuminate possible research areas for those who are new to the field or are developing new and improved control strategies.

In the article, the definition of control strategies for exoskeletons and exosuits is first discussed in the second section. According to the implementation method and corresponding research results, the control which belong to one of the three control categories was analyzed in detail. In the third section, the advantages and potential disadvantages of various control methods are put forward. Finally, in the fourth section, the possible best control method combination and future research directions are discussed and suggested.

2. Control strategies

Control strategies determine the general behavior of exoskeletons. Emphasis is placed on developing different control strategies of exoskeleton to realize more accurate intention identification, more effective control methods and improve user's ease of use. According to the hierarchical order of the hip exoskeleton and exoskeleton suit in the control schematic diagram, various control strategies of hip exoskeleton and exosuits are analyzed. Each can be categorized among one of the three levels: high-level control, mid-level control, and low-level control.

The high-level control determines the intention of the user based on either the input from the user or data collected from the user's movement. The command of a state change is passed from the high-level controller to the mid-level controller. The mid-level controller ensures safe, constant, and stable interactions between the user, device, and environment by targeting desired trajectories of the exoskeleton. It calculates the difference between the user's detected state and the desired state and adjusts parameters of the low-level controller. The low-level controller executes com- mands from the mid-level controller and prompts actuators to perform desired motions. Some also provide feedback to higher-level controllers. All powered exoskeletons and exosuits contain either high-mid-low or high-low control schematics, but this study only focuses on the novel design of one level.

2.1. High-level control

The high-level controller determines the appropriate operation profile based on the user's decision or change in activity. It determines the best operation modes to suit the user's purpose. For a hip exoskeleton, the change can be initiated manually based on conscious input from the user or automatically based on the user's motion. Recent re- search usually focuses more on automated control such as movement recognition since it operates faster and easier than manual inputs.

2.1.1. Explicit user input. The user can use an input device such as a button or switch to select the operation mode manually based on the desired task. Wu et al. [11] put forward a method which is used to assist ascend/descend stairs and level-walking. Different walking characteristics are identified by a mode-based transition gait phase estimator. Two buttons are used to control stop/go and task change. A hand-held switch is used to change operation modes when a new gait task is needed to be performed. For example, when the user needs to ascend stairs, a stair ascending button input is needed when a heel is lifted. The exoskeleton will provide assistance based on the input and recognized motion pattern.

2.1.2. Movement recognition. The control profile can be changed automatically based on the user's hip and leg movements. Using sensors embedded in the exoskeleton and/or on-board IMUs, the movements of the user can be recognized automatically. Chen et al [12] proposed a control method that automatically recognized the user's lifting technique. Embedded encoders on an active pelvis orthosis (APO) records hip angles while a 9 degree-of-freedom IMU calculates roll and yaw angle of the user. Hip angle is used to detect the lifting motion, and inertial measurement unit data is used to classify the lifting motion by using a quadratic discriminant analysis classifier. Different lifting techniques such as squat lifting, stoop lifting, and asymmetric lifting are recognized.

2.1.3. EMG control. Electromyographic (EMG) signals are biological signals that measure electrical activity when a muscle is stimulated. The data can be used to predict the user's intention to move, since the signals are sent directly from the central nervous system. EMG controlled hip exoskeleton has been proven to better reduce hip muscle activation and metabolic cost compared to traditional torque control. In Young et al [13], metabolic cost is compared between a surface electromyography (sEMG) controlled and a torque-profile controlled hip exoskeleton. sEMG electrodes are used to provide muscle activation signal to a proportional myoelectric controller, while hip extension/flexion assistance is activated using gluteus maximus EMG and rectus femoris EMG respectively. Data collected by walking tests show that the metabolic cost is reduced by 13% on average, which is 6% more than that controlled by a state machine. Participants also generally prefer the EMG controlled hip exoskeleton due to its smoother motion and higher predictability.

2.2. Mid-level control

The mid-level controller receives commands from the high-level controller and constantly changes model parameters to calculate desired positions and joint torque. The calculated parameters are sent to the low-level controller for actuation. Most research on controls was dedicated to mid-level controls since it directly determines the user-exoskeleton interaction. This section is divided into two parts: detection layer for gait state estimation and action layer for actuator control parameters.

2.2.1. Adaptive oscillator. Many auxiliary exoskeletons are controlled by adaptive oscillators. The system recognizes a periodic signal as input and changes its parameters according to the frequency. It utilizes the periodic properties of gait to understand various information of the gait cycle such as gait percentage and frequency. An adaptive oscillator-based control was proposed in [14]. Hip angular velocity as well as IMU data are used for recognizing gait phase via an adaptive oscillator. Walking states can also be recognized by comparing oscillator vectors according to a circular zone. By using angular velocity data, the adaptive oscillator can achieve 100% gait segmentation accuracy. An improved method is proposed in [15]. Instead of using sine waves functions, an adaptive oscillator with special shape is developed, which estimates the gait phase by using the specific shape of joint angle locus.

2.2.2. Linear gait phase increase. The gait phase can be easily determined by simply increasing the gait phase linearly. An event, such as a heel strike, marks the beginning of the gait phase cycle. The actuator will exert momentum according to the linearity of the gait phase, assuming that the length of each step is constant. A hip exoskeleton powered by a pneumatic system was designed [16]. An instrumented force treadmill that measures ground reaction forces is used to detect heel strikes. Throughout the experiment, participant will walk at a constant speed according to the selected rhythm. When heel contact is detected, the timing begins. The step duration is estimated through the cadence and the gait cycle percentage is determined. The pneumatic pressure will provide momentum during predefined hip extension/flexion windows and torque profiles.

2.2.3. Time-interpolated gait phase. By walking at a constant speed, the duration of previous steps is used to calculate the duration of a gait cycle. A foot switch is used to determine the start of a walking sequence in [5]. A heel strike can be detected by the foot switch and an average stride time is calculated using the previous 10 strides per leg. The pneumatic actuators will be actuated during a predefined gait cycle percentage to match a predefined hip momentum curve. Panizzolo et al., [13] designed an exosuit driven by Bowden cables. IMUs are mounted on the anterior thigh of each leg. Maximum hip joint flexion angle is used as the trigger factor of the starting device. Due to the varying nature of hip movement, the controller uses force profiles of previous steps to manage the assistance level of the actuators for constant force delivery.

2.2.4. Event trigger. Sensors that are either embedded in the exoskeleton or worn by the user can be used to detect the start of a gait event. Heel strike detection is a common method to indicate the start of a gait cycle. In [18], heel strikes are detected by force sensitive resistors placed on the heels of the user. Heel contact is defined as 0 percent gait phase and hip flexion/extension torque is exerted based on the gait cycle. A biological torque controller uses data from multiple heel strike events to record average strike duration, current gait phase percentage and reference appropriate torque profiles. Measuring ground reaction force is a similar method used for estimation. In [13], ground reaction forces are measured using a treadmill with 6 DOF force plates. Based on the increase and decrease of ground reaction force and threshold triggering, the ground reaction force distribution is standardized by using the user's weight and the recognized standing posture stage. The torque curve will be transformed in each stage, which provides references for driving the exoskeleton. An active pelvis orthosis that uses hip kinematics such as maximum hip flexion/extension is developed to accurately estimate the gait phase based on predefined profiles [19].

2.2.5. Machine learning. Machine learning enables algorithms to learn and improve from data without additional explicit commands. It has a significant advantage compared to traditional methods such as torque profile reference, since the machine learning algorithm can adapt to the complex settings of real-world scenarios and automatically adjust according to the user’s motion. In [20], real-time machine learning models are implemented in the exoskeleton processing system. Gait phase and gait percentage can be estimated using a neural network model and torque profiles are generated using the provided information. Under different walking conditions, the estimation error of gait phase generated by machine learning method is much smaller and the estimation is more accurate when the user's walking speed changes. The conclusion is that training with various data sets can make the machine learning algorithm closely adapt to the real-world scenarios.

2.2.6. Finite state machine. A finite state machine is an abstract machine that can only be in one state among a finite number of other states. It enables the control system of an exoskeleton to switch between different states, providing corresponding assistance when needed. Various sensor data can be used to trigger a state change. In [13], a state machine controller is designed to provide a torque curve similar to the torque curve of the biological hip. Different gait phases are recognized through ground reaction force using an instrumental treadmill. The exoskeleton will provide torque assistance only during early stance state and late stance state, where the control recognizes state changes by measuring the difference in force signals of the treadmill. Other controls use hip extension and flexion angle to determine the state of walking intention. In [21], a comparison method of motion sequences is developed using maximum hip flexion angle, maximum hip extension angle and angular velocity during gait shift. By comparing the changes of hip angle, we can identify two stages, standing stage and swinging stage, and apply torque assistance accordingly.

2.2.7. Torque profile. Torque profile is the most commonly used method for exoskeleton assistance. The exoskeleton can use a predefined normal biological torque profile as reference when providing assistance. An event usually marks the start of the gait phase. In [18], heel strikes are detected by force-sensitive sensors, and the beginning of a gait cycle is determined. Referencing biological hip moment profile can be fine-tuned for better assistance results. In [14], individual referencing torque profiles are used for different walking states. Automatic switches in walking states are achieved by continuously estimating the gait phase. In [22] and [23], several torque profiles are modified for different walking cadences and used for reference, which are implemented in both hip exoskeletons and hip exosuits.

2.2.8. Impedance/admittance control. An Exoskeleton with impedance/admittance control does not always provide active assistance according to a predefined contour. On the contrary, it will remain in zero impedance/zero torque mode until assistance is needed. In [4], an admittance shaping-based control is designed such that the exoskeleton will remain in a zero-torque mode until the admittance of the system exceeds the natural impedance of the human leg. SEAs are programmed to realize zero-torque mode by compensating for the intrinsic impedance and the friction of the exoskeleton. A controller based on admittance shaping is also used to ensure accurate force transfer during the assistance. An exosuit using switching admittance-position control is proposed in [24]. In the outer admittance control loop, virtual admittance is calculated using virtual inertia, damping, assistive force and desired Bowden cable velocity. Suite stiffness and thigh motion models are also implemented for better tracking performance.

2.2.9. Muscle activity amplification. The principle of muscle activity amplification is similar to that of EMG. Sensors placed on muscles can detect either the voluntary movement of the user or signals sent from the central neural system to the muscle. In both [13] and [25], sEMG signals from various leg muscles are recorded using surface electrodes. The control system will provide assistance during a specific window based on signals from specific muscles. In [26], capacitance sensing is also used. Flexible copper capacitive electrodes are placed on the inner posterior of the exoskeleton. Corresponding reference electrodes are placed on the user's skin. Muscle volume changes during muscle contraction and relaxation result in capacitance changes between the sensors. Detected muscle movement and the corresponding signal are used to estimate the phase of the gait cycle.

2.3. Low-level control

Low-level controllers work closest to the actuators in the exoskeleton and exosuit system. Using parameters sent from the mid-level controller, it can track desired parameters and enable stable interaction between the system and the environment.

2.3.1. Open-loop torque control. In [24], a feed-forward model is proposed to compensate for the nonlinearity of soft materials of the exosuit. First, a switching admittance position control is proposed. By using the signals collected from IMUs, the control schematic can be switched between admittance control and a position control loop. A feedforward model is then added to the admittance control, which uses suit stiffness model, thigh motion model and actuator transmission model to improve tracking performance.

2.3.2. Closed-loop torque control. Closed-loop torque control is used in most exoskeletons. In [27], closed-loop torque control is used to ensure the exoskeleton can produce enough torque to harmonically move with the user's leg. In [3], a closed-loop feedback control is used to ensure the exoskeleton will provide as little resistance as possible during non-assisting moments. The interaction force between the exoskeleton joints and the body is measured using force sensors placed at the active joints. The assisting force is kept close to the desired target using man-machine interaction force data and adjusting actuator torque continuously.

3. Discussion

This section analyzes the advantages and disadvantages of each control methods.

3.1. *Explicit user input*

Advantages of explicit user input include that the user has direct control of the exoskeleton's mode of operation, which greatly improves the predictability of the exoskeleton. It is also easier to implement compared to other algorithm-dependent methods. However, disadvantages include that the user needs to manually select the operation method, which presents the probability of human errors even with sufficient training. When both hands are occupied, users may find it difficult to operate.

3.2. *Movement recognition*

It enables the exoskeleton to recognize movement intentions automatically without any additional input from the user or environment. As a result, sensors already installed on the exoskeleton can be used to measure hip angle, velocity, etc., which can usually provide enough information to estimate gait. IMU units are also relatively cheap to purchase, thus lowering the construction cost for the exoskeleton. Disadvantages include that there is usually some time delay between recognition and action, which may lead to inconsistencies during continuous motion.

3.3. *EMG*

Using EMG signal for control has several prominent advantages. It can closely follow the motion intent of the user, provide smoother motion, lower peak joint momentum, and lower metabolic cost [25]. It also makes the exercise more user-friendly because the auxiliary potential and the driving time of hip joint are calculated step by step [13]. Some disadvantages of EMG control also need to be considered. Due to the number of cables and sensors needed to monitor real-time data, most EMG controlled hip exoskeletons are only used in controlled environments, where able bodied subjects perform linear tasks, which are much less complex than real-world environments. EMG signals are prone to noise interference due to electrode position, muscle fatigue and sweat on the surface of measured area [28]. EMG control is also considered to be less stable by some user since the parameters of each step changes, unlike static gait phase models [13].

3.4. *Adaptive frequency oscillator*

Adaptive oscillator has the advantage of being very robust. Periodic signals generated by the user's walking motion already provides enough information for gait phase estimation. As a result, it does not require a specific gait model and various walking speed can also be recognized.

3.5. *Linear gait phase increase*

This method has the advantage of being easy to implement. A sensor only needs to detect an event for actuation onset timing and the system will follow predefined parameters throughout the gait cycle. A disadvantage includes that the user is required to walk at a constant speed. If the step duration is not constant, the auxiliary timing can be interrupted, and inconsistency will be introduced in motion.

3.6. *Time-interpolated gait phase*

Using EMG signal for control has several prominent advantages. It can closely follow the motion intent of the user, provide smoother motion, lower peak joint momentum, and lower metabolic cost [25]. It also makes the exercise more user-friendly because the auxiliary potential and the driving time of hip joint are calculated step by step [13]. Some disadvantages of EMG control also need to be considered. Due to the number of cables and sensors needed to monitor real-time data, most EMG controlled hip exoskeletons are only used in controlled environments, where able bodied subjects perform linear tasks, which are much less complex than real-world environments. EMG signals are prone to noise interference due to electrode position, muscle fatigue and sweat on the surface of measured area [28]. EMG control is also considered to be less stable by some user since the parameters of each step changes, unlike static gait phase models [13].

3.7. Event trigger

Advantages of event triggers include the exoskeleton does not rely on multiple sensors. Most exoskeletons already have onboard sensors to measure information such as hip angles and additional force sensors are relatively easy to implement. IMUs are also widely used to measure the movement of the user, which sometimes provide enough information to estimate the gait phase. Including the disadvantages, the behavior of exoskeleton under different conditions is not clear. Experiments are usually carried out on a treadmill with a flat surface and controllable speed. If the gait cycle of the user is not periodic, methods developed for constant-speed walking will experience inconsistencies.

3.8. Machine learning

The machine learning algorithm can enable the exoskeleton to adapt to the constantly changing environment of the real world and walking speed of the user. It can also provide assistance suitable for the user's personal data. However, it is still necessary to manually select the appropriate algorithm, and first, it is necessary to train the neural network of the system, which takes time and resources.

3.9. Finite state machine

The control can automatically recognize a specific state during motion. If different force profiles are used for each state, more stable and personalized assistance can be achieved. It also does not require the user to walk at a constant speed, and it can adapt to the sudden changes of walking speed, thus improving its functionality.

3.10. Torque profile

Advantages of a torque profile include that it is easy to implement. Normal torque curve of hip joint can be easily obtained on the Internet. Data can also be modified to meet the specific need of the user. The disadvantage includes that a normalized torque profile usually needs to be calibrated to achieve the best assistance result, since each person has unique hip kinematics.

3.11. Impedance/admittance control

Advantages of an impedance controller include providing help only when necessary. This can improve the rehabilitation effect since the user’s leg acts as an active component of the human exoskeleton system instead of being a passive component. The stiffness and damping parameters of the system can also be changed to best achieve the desired effect.

3.12. Muscle activity amplification

Advantages include that the user’s intent to move can be recognized before the movement starts. This enables the exoskeleton to closely synchronize with the user. Some disadvantages include that the process of setting up EMG sensors can be lengthy and complicated. Extra wires that need to be put on the user will present difficulties in daily use. Muscle fatigue will also pose problems during long walking sessions since a weaker signal will increase the error of the detection method. People with neurological disorders and impairments are also not suitable for EMG signal detection.

4. Conclusion

This paper analyzes the article that puts forward a new method for controlling the exoskeleton of hip joint and exoskeleton. These comparisons are classified according to a rank order. The methods of implementation as well as the advantages and disadvantages of each method were also analyzed. Furthermore, the recommended best combination of control methods was proposed for future references.

Motion recognition has been proven to be the best high-level control method for both exoskeletons and exosuits. Due to the control's autonomous nature, it is easier for the user to operate compared to manual inputs and is generally more reliable compared to the complexity of EMG control. The adaptive oscillator may be the best method for mid-level detection. It operates based on the oscillating nature of the gait phase, which enables it to provide smooth assistance for the user and is easier to implement compared to other control methods. The action layer of mid-level control benefits most from impedance/admittance controller since it only delivers assistance when needed, making it great for gait training and rehabilitation. In the low-level control, exosuits usually adapt open-loop torque control. Due to the flexible nature of the exosuit, disturbances introduced by the user and environment can be compensated effectively. Closed-loop control mostly benefits hip exoskeletons. When combined with impedance and admittance controller, it can achieve accurate force measurements due to fast, accurate force delivery and high stiffness of the exoskeleton.

For future studies, more articles on exoskeleton and exosuit controls can be analyzed to expand the scope of each control level. Each article can be categorized based on its proposal for novel control methods or improvements to existing methods. It is possible to conduct a more comprehensive study on a specific control level. The actuation systems of exoskeletons can also be analyzed since their power delivery methods and efficiencies directly affect the performance of the human-exoskeleton system [29].

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