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High-level control architecture of lower limb exoskeleton: A review

Haonan Zhou

Mechanical Engineering, SWJTU-Leeds Joint School, 611756 , Chengdu, China

453432716@qq.com

Abstract. As a rehabilitation robot for aiding in the movement of lower limbs, the lower limb exoskeleton is a beneficial device. In order to make the most effective use of the exoskeleton, the control strategy plays a crucial role. This review paper provides a background and classification of lower limb exoskeleton control strategies, such as model-based and hierarchy-based control. Further, we presented mainly the high-level control architecture of lower limb exoskeletons, which is aimed at detecting the intention of human movement. An in-depth discussion is provided in this paper regarding manual user input (MUI), surface electromyography (sEMG), and brain-computer interface (BCI). Many people need exoskeletons, which is why this review was written. Exoskeletons, however, are expensive and cannot be mass-produced, and their control methods are immature, making them ineffective. Thus, the objective of this review is to identify research gaps and common limitations in previous research to obtain future directions for improving the usability of the control mechanism. In an alternative approach, MUI and BCI are combined to reduce the time spent switching movement modes and the amount of concentration required to do so.

Keywords: Lower limb exoskeleton, control strategy, high-level control, manual user input, brain-computer interface.

1. Introduction

Many Chinese people, especially the elderly, suffer from various movement disabilities due to ageing and spinal cord injuries, which will add to their physical and mental stress and financial stress [1]. This exoskeleton is regarded as a rehabilitation robot consisting of both upper and lower limb exoskeletons. The lower limb exoskeleton is primarily used to solve patients' movement problems. However, the existing control strategies for lower limb exoskeletons are insufficient to assist patients in their rehabilitation process. In order to meet future needs, they should be optimized. Consequently, the technology domain presented in this paper is the control strategy of the lower limb exoskeleton.

In recent decades, several control strategies have been developed for the rehabilitation of lower limb exoskeletons, including trajectory planning, control systems [2], admittance shaping, oscillator-based control [3], and assist as needed control (AAN) [4]. Additionally, numerous review papers have summarized and categorized these control strategies over the past few decades. Anam and Al-Jumaily [5] distinguished four control systems: model-based, hierarchy-based, physical parameter-based, and usage-based control systems.

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Tucker et al. [6] developed a broad picture for controlling lower limb exoskeletons. In [6], a systematic hierarchical classification was proposed based on research conducted by Varol et al. [7], as shown in Fig. 1 [8]. It is still the most common method of classifying lower limb exoskeleton control strategies, referred to in recent reviews. For instance, Al-Shuka et al. [9] detailed three levels of control strategies in biomechanical considerations supported by many theoretical equations and logic diagrams, and Baud et al.[8] summarized the strategy in the aspect of advanced technology such as brain-computer interface (BCI) and terrain identification (TER).

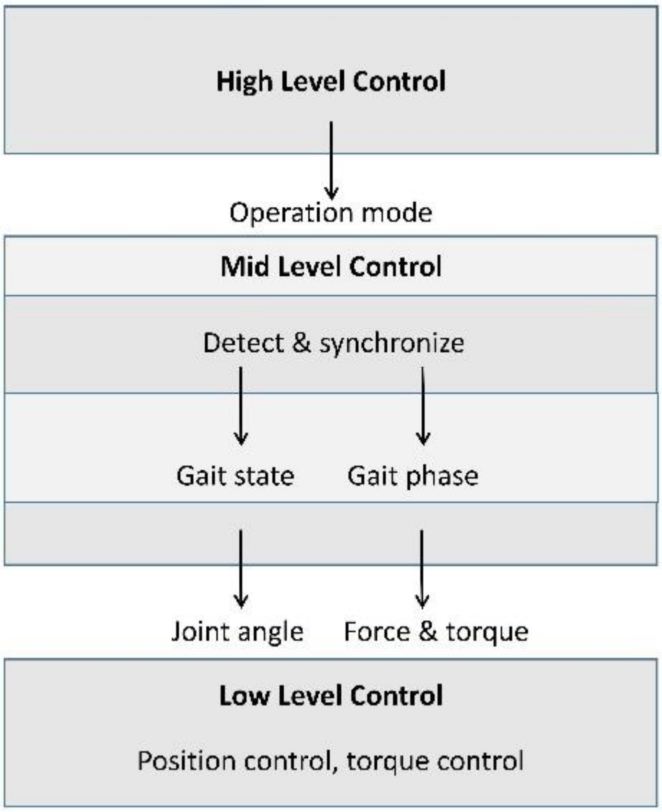

Figure 1. Three levels of control mechanism. Adapted from Baud et al. [8].

Even though many articles summarize control strategies using the three-level method, few articles are dedicated to high-level control and analyze it in detail. The term "high-level control" refers to various techniques designed to recognize the intention of the human movement or the dynamics of the surrounding environment and adjust the exoskeleton's operating modes accordingly. In 2018, Al-Shuka et al. [10] presented a summary of high-level control strategies based primarily on electromyography (EMG) techniques to identify human walking intent. Nevertheless, the field of artificial intelligence, including brain-computer interface, has rapidly developed in recent years and continues to evolve. Hence, review papers from a few years ago are no longer persuasive because they lack a summary of advanced technologies. Therefore, it is necessary to reorganize the high-level control strategies. The classic control methods within the high-level control strategies are discussed throughout the paper.

Following is an outline of the remainder of this paper. Section II describes the categories of mainstream exoskeleton control at a high level. The introduction and drawbacks of the three high-level control strategies, manual user input, surface electromyography technique, and brain-computer interface, are presented in sections III, IV, and V, respectively. In Section VI, we re-emphasize existing control strategies' drawbacks and limitations. As a conclusion to this paper, Section VII discusses the challenges and alternative future directions in this field.

2. Categories of High-level Control

As aforementioned, high-level control of the lower limb exoskeleton, regarded as the perception layer [6], is the basis of mid-level and low-level control. Nowadays, there is no direct and effective method to perceive human intention. The most common methods are explicit and manual user input (MUI) because these kinds of input devices, such as voice commands [11] and buttons [12, 13], are easy to implement. Besides, in 2006, Fleischer and his colleagues [14] applied the EMG techniques to the leg exoskeleton, which was proven experimentally effective. Their work concluded that EMG could provide exceptional performance without elaborate dynamic models. However, the EMG parameters had to be calibrated at the beginning of each experiment, which means this device was not practical.

Additionally, Sankai [15] proposed that bioelectrical sensors applied to EMG can successfully perceive human intention. However, those are unsuitable for patients with neurological impairments that cause walking problems. Surface EMG (sEMG) is another method that can be used to perceive human movement [16]. It is better and more convenient than EMG because it only requires the sensor to be placed on the skin's surface. Furthermore, with the rapid development of brain-computer interface (BCI) technology, BCI is also gradually being used in controlling devices to assist [17]. Electrodes can detect human brain activity to determine the operating mode. He et al. [18] systematically reviewed brain-computer interfaces for the lower limb exoskeleton, which indicated that the BCI system is promising but immature due to the small sample pool and potential safety risks.

Hence, the categories of mainstream high-level control strategies can be divided into three main divisions: Manual user input, surface electromyography technique, and brain-computer interface.

3. Manual User Input

As mentioned above, MUI consists of devices such as buttons [12, 13] and voice commands [11]. They are prone to implementation, have higher predictability, and have lower error risks. Hence, it has become the most common control strategy for the lower limb exoskeleton.

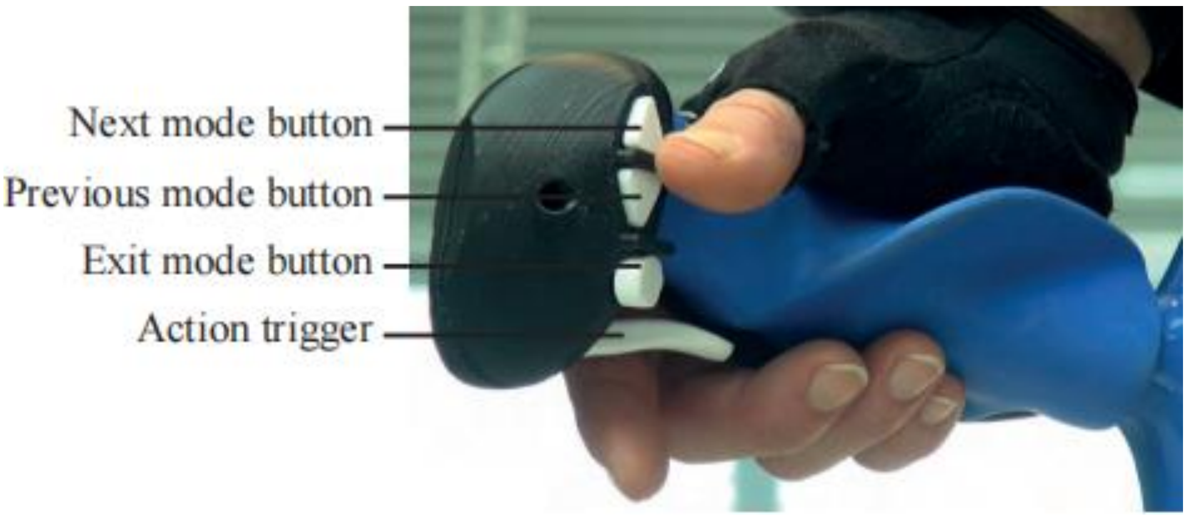

Figure 2. Crutch remote with three buttons and one trigger [12].

For example, TWIICE, introduced by Vouga et al. [12], has a user interface designed to be as simple as possible. It is on the front end of the right crutch for a user to control the exoskeleton, as shown in Fig. 2 [12]. This button layout allows users to access the three buttons with their thumb and trigger with the index finger while holding tightly to the crutch.

The exoskeleton has many movement modes: slow/fast gait, sitting down, stairs ascent/descent, and variable step length. In either mode, the trigger button must be pressed once for each action performed, even a simple step. For instance, under the mode of sitting down, the exoskeleton starts transiting to the sitting position once entering this mode. If we press the trigger, the exoskeleton will begin standing up slowly, and pressing again can abort standing up and sitting down. Besides, the controller will read the foot load cells before each step to validate that the stance leg's main body weight is supported [12].

Additionally, Kagirov et al. [11] designed a voice interface for the medical robotic exoskeleton "Remotion" based on the Android OS's open-source software, and its module is Java-based. Voice input can significantly improve the effectiveness of controlling the exoskeleton. It is because voice input is faster and less distracting to the user than touch control. ExoAtlet exoskeleton by Exoatlet Ltd. and ARKE exoskeleton by Bionic Laboratories Corp. have realized the application of voice input in their control. For "Remotion", voice commands currently available to the user are shown in Table 1 [11].

Nevertheless, button control and voice commands are not practical in real life. These technologies are not innovative enough; they increase the user's cognitive load, and the long time intervals required to perform actions make them less natural. In addition, it is difficult for users to use the exoskeleton while doing other distracting things, such as talking on the phone or listening to a song. In noisy outdoor environments, voice control is also impossible and can embarrass people.

4. Surface Electromyography Technique

The surface EMG technique can effectively improve the efficiency of controlling the exoskeleton. It is because the EMG signal is only related to the user's muscle activity and is not influenced by the environment in which it is used [14].

EMG can be used to determine the activation state of a muscle by measuring the EMG signal generated by movement neurons stimulating muscle fibres. In addition, the EMG signal signature allows us to analyze the muscle's force and the joint's torque [19].

Table 2. Voice Command List [11].

Voice command (in Russian)	Actuation performed by the exoskeleton
'Take a step'	One step forward
'Go'	Continuous steps forward
'Stop'	Keeping a standing position
'Get up'	Getting up from a sitting position
'Sit down'	Take a seated position
'Turn left'	Turning left 90°
'Turn right'	Turning right 90°
'Abort'	Cessation of the last active actuation

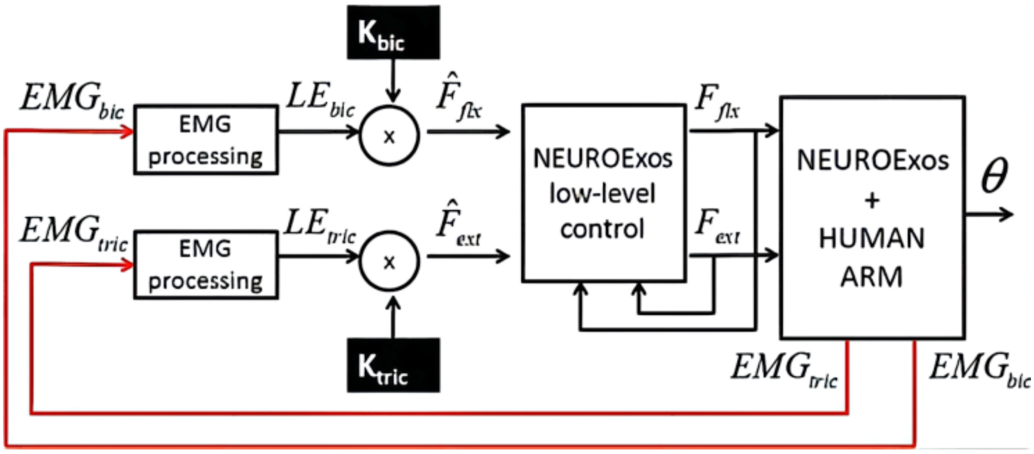

Figure 3. Block diagram of the proportional EMG control system [20].

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Lenzi and his colleagues designed a closed-loop EMG-based control system, as shown in Fig. 3, and used it on the NEUROExos platform to control an elbow-assist exoskeleton. The device provides the user with a torque proportional to the strength of muscle activation to assist the user with movement. They placed bipolar surface electrodes on the skin surface of the biceps and triceps to measure EMG activity and used the EMG signal as a drive signal for the controller in the control system to determine the effort expended by the muscle during exercise. Experimental results showed that the exoskeleton effectively reduces the effort the muscles spent under different gain conditions ($\mathrm{K_{bic}}$ and $\mathrm{K_{tric}}$), regardless of whether the user is in the unarmed or weight-lifting state. A similar control system could be applied to the lower limb exoskeleton control strategy [20].

Furthermore, Kiguchi et al. [21] combined two other kinds of EMG-based control methods, the neuro-fuzzy and muscle-model-oriented control methods, to complement the disadvantages of both approaches. The muscle-model-oriented control method can stably make the real-time estimation of users' lower limb motion. However, limb gestures can negatively affect it. Therefore, the neuro-fuzzy modifier is used to adjust the weight matrix to effectively compensate for the effect of lower-limb posture difference. Moreover, the muscle-model-oriented method is reliable when the degrees of freedom (DoF) of movement increase. In the other method, increasing DoF would complicate the control method. The architecture of the neuro-fuzzy muscle-model matrix modifier is shown in Fig. 4 [21], which proved effective in their experiments.

However, the effectiveness of this method depends on the condition of both the skin and the muscle, as well as the location of the electrodes on the skin surface. Therefore, further optimization of the surface EMG technique is needed before it becomes universal and practical.

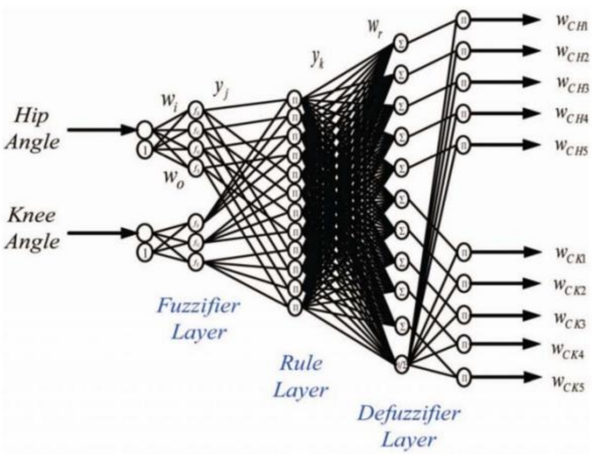

Figure 4. Neuro-fuzzy muscle-model matrix modifier [21].

5. Brain-Computer Interface

Brain-computer interface is a scientific method of translating brain signals into user intent. Brain signals are recorded through electrodes, filtered and classified, and compared to samples in a database to determine the user's intent. With the development of the brain-computer interface, this technology is also increasingly used in assistive devices [17]. Currently, there are two main methods for obtaining brain signals: the first method involves the use of intraparenchymal electrodes to identify local field potentials within the brain by recording signals under the skull using an electrocorticogram (ECoG), while the second, more widespread method uses non-invasive electrodes placed on the scalp in order to gather a global perspective on brain signals [3]. Unfortunately, EMG could not be used here because the EEG signal was only close to 100 microvolts. In contrast, the EMG signal range is approximately several millivolts [8]. Nazeer and Naseer [22] depicted the process of the BCI system, as shown in Fig. 5, pioneered the use of functional near-infrared spectroscopy (fNIRS) to differentiate brain signals into motion and rest and successfully enabled the control system to have better performance.

However, this approach has several drawbacks, such as fewer executable commands, difficulty installing electrodes, and the requirement for extreme concentration on the user's part, which will need to be addressed in future research.

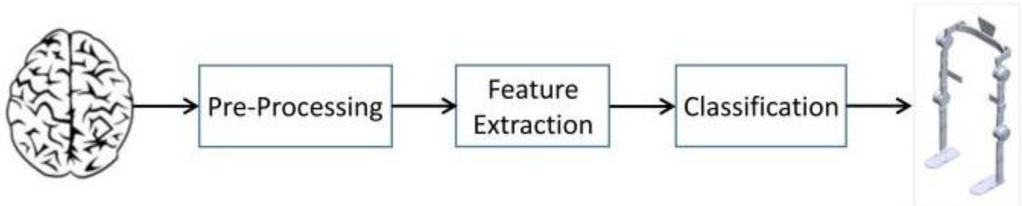

Figure 5. Typical BCI system [22].

6. Discussion

So far, little research has been conducted on high-level control for recognizing human movement intention [8]. It is vital and inevitable that patients frequently change their working patterns to adapt to different working environments depending on their movement intentions.

The main contribution of this article is to summarize and introduce the dominant control methods in lower limb exoskeleton control strategies: manual user input [11]-[13], surface electromyography [14], and brain-computer interface [17]. All three control strategies, however, have certain limitations, as discussed in the previous section. Currently, the technology is in the laboratory testing stage and is not yet mature enough to be used in practical applications. The MUI and BCI control methods involve fewer commands in general. Moreover, both require the user's concentration, which makes it difficult to operate the exoskeleton while performing other tasks. Furthermore, the voice control in the MUI is not even usable in noisy outdoor environments. Even though surface EMG technology does not require concentration and is unaffected by environmental conditions, its effectiveness is dependent on the complex conditions of the body's muscular surfaces, which results in tedious parameter tuning before each use of the exoskeleton, leading to poor generalizability.

For this reason, future research should optimize high-level control strategies for lower limb exoskeletons.

7. Conclusion

This paper summarizes the high-level control strategies for lower limb exoskeletons: manual user input, surface electromyography, and brain-computer interface, and briefly discusses their advantages and disadvantages. The field can still not effectively control lower limb exoskeletons following human intentions in daily life. A challenge lies in adapting to complex environments and making them seem more natural and senseless to the user.

Future research could focus on applying different control strategies within a single control system. There is no doubt that BCI requires a high concentration level and has a short time for mode switching. The MUI, on the other hand, does not require as much concentration after the user has become proficient, but the time required for mode switching is longer. As a result, we may be able to combine these two methods in future research: The BCI forecasts changes in the movement environment and determines whether a change in activity mode may be necessary before preparing the movement control commands for the exoskeleton. The MUI is used to perform a one-touch operation after walking to the location where the operation needs to be switched. The solution reduces the time it takes for the exoskeleton to change modes and makes it more practical to use in complex and less focused environments.

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