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Control methods for intelligent prosthetics based on human-machine interaction

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Abstract. Intelligent prosthetics play a crucial role in restoring social functions for people with disabilities. This paper systematically reviews the decoding techniques for motor control information used in intelligent control of prosthetics and the encoding techniques for sensory feedback. The acquisition and decoding of motor information are discussed in terms of signal recording and decoding from the human body and the prosthetic. Sensory feedback in prosthetics is discussed from the perspectives of biomimetic and non-biomimetic feedback. Finally, the development of intelligent prosthetic control is explored, summarizing and forecasting future directions in this field.

Keywords: Assistive Technology, Intelligent Prosthetics, Electromyography, Electroencephalography, Sensory Feedback.

1. Introduction

Individuals with amputations or congenital deformities typically face limitations in upper and lower limb functions. Intelligent prosthetics, as assistive devices, can effectively help these individuals overcome daily mobility barriers, improve quality of life, reduce existential and appearance-related anxieties, and facilitate better social integration while mitigating discrimination [1]. Intelligent prosthetic technology employs a multidisciplinary approach integrating biology, mechanics, and electronics to simulate biological systems through mechanical design. This technology consists of recognizing and decoding human movement intentions, algorithm computations, and closed-loop control [2,3]. The recognition and decoding of human movement intentions, and the feedback in closed-loop control, are crucial for achieving a complete human-machine interaction loop. Recognition and decoding involve capturing a variety of signals such as bioelectrical signals [4], biomechanical signals, and complex environmental signals [5], processing these signals to decode human movement intentions. Research on diverse signal collection and decoding to improve the accuracy of recognizing human intentions and execution precision in complex environments is essential. Sensory feedback in prosthetics involves relaying the prosthetic’s operational status and environmental changes to the human body through stimuli, such as electrical stimulation [6] and vibratory stimuli [7], allowing for real-time perception of the interaction between the prosthetic and the environment, thus achieving true closed-loop control in human-machine interaction. Ideally, feedback would replicate natural physiological sensations through multiple channels. However, current prosthetic feedback often relies on compensatory mechanisms such as visual and auditory feedback, which still significantly differ from natural human tactile and proprioceptive sensations.

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This study focuses on two main aspects of human-machine interaction control in intelligent prosthetics: the recognition and decoding of human movement intentions and the feedback of sensory signals. It discusses motor information collection and recognition from the perspectives of human-machine interaction control and assistive control technologies in intelligent prosthetics, while sensory feedback is introduced from the perspectives of physiological alignment and sensory modalities for the missing limb. The current state of human-machine interaction in intelligent prosthetics is analyzed and discussed.

2. Acquisition and Decoding of Motion Information

2.1. Human-Machine Interaction Control Technologies for Intelligent Prosthetics

Neural electrical signals such as electroencephalography (EEG) and electromyography (EMG) reflect the activities of the central nervous system. Collecting and decoding EMG and EEG signals based on human motion intentions allow users to autonomously control intelligent prosthetics, further enhancing natural human-machine interaction through various artificial intelligence control algorithms.

The acquisition of EMG signals can be categorized into implantable and non-implantable methods. Implantable measurement of EMG signals requires less specific muscle conditions and offers advantages such as low interference and high recognition rates compared to surface EMG signals, providing in-depth analysis of the bioelectrical characteristics of different motor units during muscle contractions. For instance, ultrasonically guided minimally invasive implantable EMG sensing technology has been adopted for more adept control of prosthetic arms in individuals with transhumeral amputations, where surface EMG signals are challenging to sense accurately [8] Innovations like the semi-implantable device invented by Becerra-Fajardo et al., which is powered and communicates via an external system and implanted through injection, significantly reduce the risk of infection while ensuring precise communication [9,10]. However, the biocompatibility and lifespan of implantable sensors still require further research and clinical validation.

Non-implantable measurements typically involve collecting surface EMG signals by placing electrodes on the muscle surface, which reflect the electrophysiological characteristics of entire muscle contractions. Analyzing surface electromyograms across different channels feeds back to the control system to achieve closed-loop control. Surface EMG signal extraction is advantageous due to its simplicity and non-invasiveness; however, the collection of surface EMG signals demands high muscle and nerve quality from users and is susceptible to interference from factors like sweat. Currently, in the realm of control algorithms, scholars have proposed the shared control theory for intelligent prosthetics, allowing amputees to achieve more precise grasping movements based on surface EMG signals [11]. Proposals for new classification frameworks suitable for upper limb prosthetic systems using fewer signal channels have been made, enhancing the performance and convenience of intelligent myoelectric prosthetics [12]. Clinical trials focus on improving robustness, simplifying channels, and enhancing algorithms, which are current research hotspots.

EEG signals can be collected through invasive or non-invasive recording systems. Although invasive methods provide more accurate and precise recognition of brain activity, sensors are surgically implanted beneath the scalp to capture neural signals. Non-invasive methods involve placing electrodes on the exterior of the head to record electrochemical pulses of various frequencies emitted by the brain, analyzing and processing electroencephalograms to recognize human motion intentions and thereby facilitate human-machine interaction. Researchers like Taha Beyrouthy have developed intelligent, multifunctional, low-cost prosthetics using EEG neurofeedback technology [13]. However, signals need to pass through biological tissues such as the skull and meninges, which greatly attenuates the EEG signals. Therefore, minimizing interference and accurately processing EEG data to recognize motion intentions are crucial. Sachin Kansal and others have used EEG data from a 32-channel EPOC Flex headgear and a deep learning model optimized by a Genetic Algorithm (GA) and Long Short-Term Memory (LSTM) to classify upper limb motion intentions, achieving accurate control over three degrees of freedom for the upper limb [14]. Luttfi A and colleagues have achieved up to 97.4% accuracy by using statistical features like Arithmetic Mean (AM), Standard Deviation (SD), and Skewness (S) and applying the ReliefF Deep Neural Networks (DNN) method for feature selection, significantly improving the processing of EEG signals compared to traditional methods, making control mechanisms more sensitive and intuitive [15].

2.2. Assistive Control Technologies for Intelligent Prosthetics

Prosthetics employ intelligent technologies to capture external information and their own biomechanical data, facilitating the operation of the prosthetic and the correction of gait. Advanced assistive technologies enable more precise intelligent control of prosthetics. Biomechanical signals primarily record kinematic and dynamic information during motion, such as joint angles, inclinations, and linear accelerations, gathered through inertial sensors. This motion data is then decoded using various algorithms to produce matched joint angles and angular velocities, reducing the response delay of the prosthetic and enhancing the accuracy and robustness of recognizing and adjusting to the patient's movement intentions [16].

For example, joint coordination based on physiological gait employs statistical regression methods to estimate missing motion using the complementary limb motion estimation (CLME) strategy to control an active knee joint device used in stair descent experiments, minimizing the prosthetic's response delay [17]. Additionally, specific trajectories set for different motion patterns are recognized and triggered by classifiers. During obstacle crossing, heuristic algorithm-based swing phase trajectory control allows the patient to maintain an appropriate knee flexion angle, increasing the clearance over the obstacle with the foot [18].

3. Sensory Feedback Technologies for Intelligent Prosthetics

In the application and testing of rehabilitation aids and prosthetics, most sensory feedback is conveyed through indirect, non-motor-related means such as visual and auditory channels. However, the human somatosensory system includes sensory receptors, afferent peripheral nerves carrying stimulus information, and somatosensory cortical areas of the brain. This system encompasses touch, pressure, temperature, itch, joint angles, and proprioception of one's own limb movements [22]. Studies have shown that rich sensory feedback not only significantly improves task performance and cognitive labor but also reduces phantom limb pain [19,20]. Therefore, researching how to sense and deliver rich feedback effects is essential for achieving integration between humans and machines.

Achieving rich sensory feedback may involve electrically stimulating peripheral nerves to induce perceptions of skin and proprioceptive sensations [21]. Using square electrical pulses on specific nerve bundles with selected electrode intensity and stimulation duration can evoke sensations of touch, joint movement, and position sense [22]. This method, using the patient's phantom mapping, electrically stimulates specific peripheral nerves to generate sensory feedback from the prosthetic. J. A. GEORGE and others have implanted the Utah Slanted Electrode Array (USEA) into the median and ulnar nerves, inducing localized sensations in the phantom hand through electrical stimulation and using biomimetic algorithms for feedback, resulting in test efficiency and accuracy far superior to non-biomimetic feedback [23]. Electrically stimulating peripheral nerves to induce tactile and other sensory information holds immense potential for development.

Non-biomimetic feedback can also be considered, using other senses to substitute for the original proprioception. For example, applying a stretching torque proportional to the gripping force at the elbow to identify the stiffness and weight of different objects, although this is only applicable for amputations below the elbow joint. Alternatively, adhesives attached to the skin can stretch the skin to provide feedback on the weight of the grasped object. Jason Wheeler and others have designed a wearable device that rotates and stretches the skin to provide position and motion state information, with errors smaller than those without feedback [24]. Or using vibrators that apply continuous varying amplitudes of vibration when the prosthetic comes into contact with an object, which can better assist patients in completing grasping tasks compared to applying vibrations of different frequencies [25]. Although non-biomimetic feedback lacks the control precision and comfort of biomimetic feedback, it often has

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advantages such as lower cost and portability, allowing for mass production. Other problems of the approaches using remapped mechano-, vibro-tactile or electro-cutaneous feedback include: artefacts on the recoding system used for the prosthesis control due to the stimulation28, the miniaturization of the systems, power consumption and the quality of the sensation elicited, which is not very pleasant.

Moreover, a new sensory feedback system can be considered from the perspective of modal matching. Modal matching is a feedback strategy that conveys prosthetic sensor information to the human body in the same modal manner, emphasizing the consistency of the physical form of the stimulus. This is achieved by replicating the original sensations at the residual limb or other areas such as the chest or the contralateral limb. In the design of today's multimodal tactile feedback systems, patients can intuitively perceive vertical forces, temperatures, and the roughness of objects. Although multimodal tactors have the ability to deliver significantly more information than a traditional single-mode feedback device, the utility of providing additional signals needs to be further evaluated.

Neither substitution nor modality-matched methods provide input through the original sensory pathways of the amputee Citation. The ideal system would combine the benefits of modality and somatotopic-matching systems to allow the participant to feel a relevant stimulus at the correct location on their missing limb Citation.

Accurate control of intelligent prosthetics initially requires active control based on human motion intentions, followed by assistive control based on deep learning, and finally timely correction based on sensory feedback, as shown in Figure 1, the flowchart of intelligent prosthetic control.

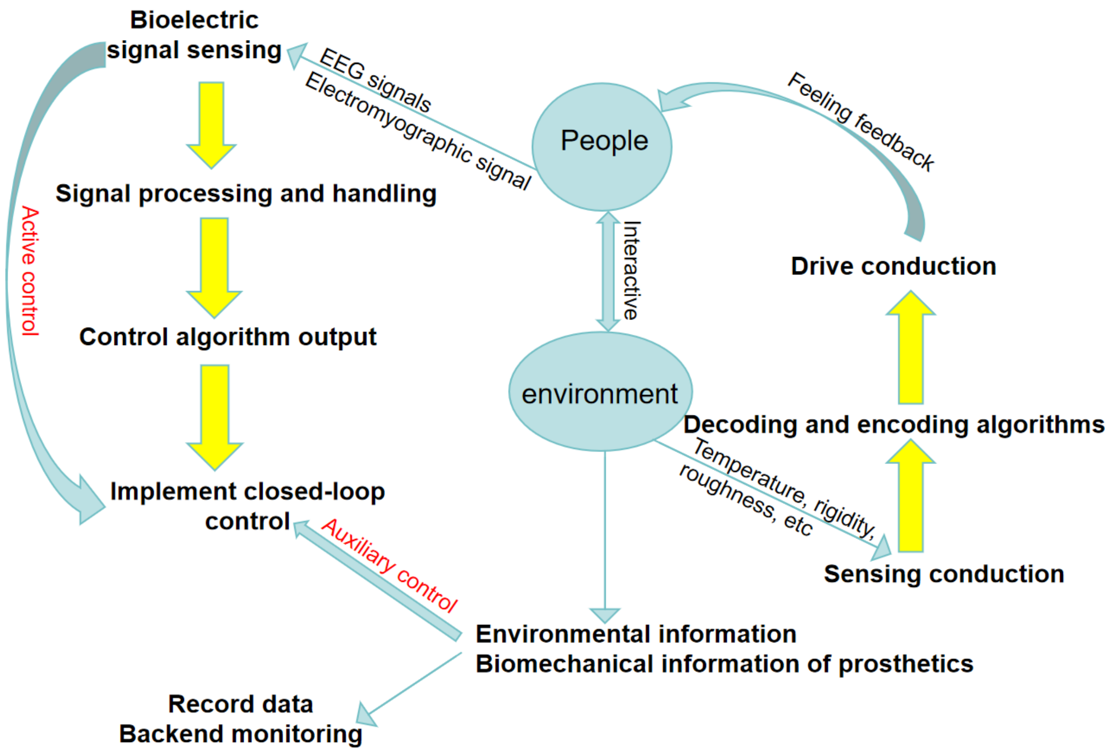

Figure 1. Flowchart of Intelligent Prosthetic Control

4. Conclusion

Intelligent prosthetic technology involves artificial intelligence and human-machine interaction, presenting numerous scientific and technological challenges that require further research and improvement by scholars. This paper aimed to introduce prosthetic control technologies based on the decoding of human movement intentions and sensory feedback. It discussed the collection and decoding of motion information from two perspectives: human-machine interaction control technology and assistive prosthetic control technology. It also introduced prosthetic sensory feedback, covering sensory substitution, sensory modalities, and the induction of sensations through peripheral nerve electrical stimulation. In the closed-loop control of prosthetics, the interaction between the output of human movement and the input of sensory feedback is crucial, and finding the dynamic equilibrium between them is key. In the future, the focus of research in the rehabilitation field will be on the biomimetic structural design of intelligent prosthetics and the integration of human-machine systems in complex environments, which will still require extensive clinical experimentation for validation.

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