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Engineering Challenges in Developing Exoskeletons for Mobility Assistance

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ABSTRACT

The development of exoskeletons for mobility assistance holds great promise in enhancing the quality of life for individuals with mobility impairments, including those affected by spinal cord injuries, stroke, and other conditions. Exoskeletons can be categorized into powered and passive systems, each designed to aid mobility, such as walking, standing, or climbing stairs. This paper examines the engineering challenges in the design and implementation of exoskeletons, focusing on key areas such as biomechanics, sensors and actuators, control systems, and power supply efficiency. Critical aspects like real-time sensor data processing, actuator selection, and energy storage solutions are discussed in detail, alongside the integration of artificial intelligence (AI) for adaptive movement control. The article also emphasizes the importance of balancing weight, power efficiency, and energy storage to ensure effective and long-lasting use in daily life. With ongoing technological advancements, these challenges are becoming increasingly addressable, leading to more functional and reliable exoskeleton systems for rehabilitation and daily assistance.

Keywords: Exoskeletons, Mobility Assistance, Rehabilitation, Biomechanics, Sensors, Actuators, Control Systems, Power Supply, Energy Efficiency,

INTRODUCTION

An exoskeleton is mainly designed to provide mobility assistance to individuals with certain mobility impairments, such as those with spinal cord injuries. According to their intended application fields, various types of exoskeletons can be found on the market. They can be classified as powered or passive according to the presence of energy input into the motion controller. The primary aims of developing exoskeletons are to help individuals stand up, walk, or climb stairs and, in general, enhance their quality of life and improve the rehabilitation process [1, 2]. The concept of exoskeletons dates back to the 1890s when a mechanized suit was imagined and called a "man amplifier." With advances in mechanics and materials, particularly lightweight materials and electric actuators that have emerged over the years, the development of technologically complex exoskeletons has become more feasible and, in many respects, more popular today. The first public demonstration of an actual powered robotic exoskeleton took place during a cybernetics conference, which entailed a simple electric arm mount. Though some are generally credited with developing the first air-powered exoskeleton in 1983, none of these early prototypes have ever been used on humans and are mainly used as proof of concept. From geography to health, their applications are divided into two categories: rehabilitation and daily assistance. The primary target of rehabilitation robots is, in general, the young population who have suffered a stroke or any kind of immune disease, while the target of daily life assistance robots is the elderly [3, 4, 5].

Biomechanics and Human Factors Considerations

The biomechanics of natural human walking and standing largely dictate the design of lower limb exoskeletons. Both the kinematics and kinetics of human walking are well described and are relatively consistent across individuals. Exoskeleton motion must be properly synchronized with human movement to achieve natural and efficient mobility, i.e., to achieve good biomechanical and energetic synergy with the user, reduce user effort, and increase user comfort. Human walking biomechanics also tend to change with exoskeleton use, adjusting from full or partial paraplegia [6, 7, 8]. However, certain aspects of lower limb walking biomechanics must necessarily be adjustable in any assistive exoskeleton design, notably the gait trajectory, the impedance profiles of the joints, and the step frequency, which must be adjustable to both fit the user and yet maintain gait adaptability when changing from sit to stand positions, etc. Both spastic and non-spastic paraplegia gait patterns develop due to a series of neuromuscular adaptations to standing and locomotion in leg impairments, and both user groups tend to develop pathological gait patterns over time that are unique to their muscle weakness patterns. Heavy emphasis on ankle and knee movement may be needed in some pathological populations. Integer and non-integer resonances are possible, which can result in any phase difference of the exoskeleton gait trajectory concerning the human walking gait trajectory. Because the stride period increases with faster walking, an assistive exoskeleton gait trajectory must also allow for step transitions that do not create a user posture destabilizing effect [9, 10, 11].

Sensors and Actuators in Exoskeleton Design

Sensors and actuators are two important parts of an exoskeleton. The sensors generate data that can monitor user movements or the surrounding environment, as well as collect the data necessary to calculate the stiffness of actuators. Depending on the application, different types of sensors can be used to monitor force, position, and acceleration, as well as environmental conditions. This data is used to adapt the exoskeleton assistance in real-time, but also to adjust the actuator stiffness according to the movement to be performed. When collaborating with actuators, sensors should be (a) made of durable materials, (b) have a high precision of measurement, (c) be small, (d) offer a connection that can be easily integrated with the rest of the exoskeleton, and (e) be mounted in surgeries without disturbing the activity of muscles. There is also a trend in the market for new sensory materials that are also used in robotic exoskeletons, such as soft sensors that are applied directly to the human skin. Sensory integration is a time-consuming process, reinforcing the need to speed up calculations related to resistance and adaptation assistance [12, 13, 14]. Actuator design has dramatically changed the way exoskeletons are conceived and constructed. Exoskeleton activation can be assisted by actuators in locked or unlocked axes that can be actuated by a DC, pneumatic, or hydraulic motor. The design depends on the type of mobility that supports the entire exoskeleton. The actuator determines both the maximum value that can be exerted as the desired torque and the maximum value of the speed. The actuators have to be chosen based on the inert mass associated with each degree of freedom, so as not to have a joint too rigid in the direction of freedom. High reciprocal interaction is necessary between the sensor system and the robotic mechanism. Unfortunately, actuators involving both the locked-axis and unlocked-axis are difficult to manage, which is why systems operate with permanently locked or unlocked actuators. It is necessary to carefully select the right actuator to match the exoskeleton support and allow redundancy in the actuator system to ensure exoskeleton mobility in special situations [15, 16, 17].

Control Systems and Algorithms for Exoskeletons

The control systems and strategies utilized in robotics and assistive technologies follow the same fundamental principles of control theory. The control systems are the mechanisms of the exoskeleton design that enable the device to function. In exoskeletons, algorithms are responsible for interpreting and processing user intent from numerous devices. The most common control strategies used in ASR are impedance control and assistance as needed. The basic working concept of the control systems algorithm is designed to identify the movement commands of the user or patient through the sEMG signals or the wearable sensors; the exoskeleton's DC motors then execute them. Therefore, to have a control system algorithm that can control the exoskeletons in closed-loop systems in real-time conditions, will be one of the practical solutions to design soft exoskeletons. The suitable solutions to overcome the limitations of the control systems in hard exoskeletons involve utilizing artificial intelligence techniques to control the exoskeleton in closed-loop systems in real-time conditions. Thus, the introduction of AI at the stage of control systems is an important factor in achieving the best power and assistive support for patients during rehabilitation programs [18, 19, 20]. The theory of regulation and control originates from behavioral characteristics, such as human perception of commands that reveal these behaviors. Nevertheless, there are challenges in analyzing this approach in practical implementations, such as the difficulty of creating exact mechanical models of the wearer, which is considered reactive and therefore not perfect for specifying anticipatory exoskeletons. It is due to the aforementioned problem that open-loop control has not been extensively employed in the development of exoskeletons and devices for mobility assistance. Real-time control is critical for exoskeleton systems to assist the user according to the movements the user performs. The fields of robotics and artificial intelligence have begun to be used in exoskeletons to learn movement patterns of both healthy and pathological gait. Exoskeleton robots are complex systems that interact with the human body. The design of the exoskeleton controls must be suitable for humans in different walking conditions. The final goal of powered exoskeletons for mobility assistance is to ensure better performance for the gait patterns of patients in various environments [21, 22].

Challenges In Power Supply and Energy Efficiency

Providing energy to the entire exoskeleton system is one of the biggest engineering challenges in the development of the overall system. This is especially the case for the wearable and hence mobile systems. With such mobile systems, the majority of user mobility support work is done by the exoskeleton's own actuators. Power for these must be mobile, stored on board. A number of portable power sources exist, but the efficiency, longevity, and mass of these sources can vary greatly, largely determining the exoskeleton's capabilities. In most walking exoskeletons, portable energy sources in the form of batteries are used. Fuel cells show promise, especially in smaller applications, but a breakthrough in compatibility is needed to fit them into a wearable exoskeleton. An overly large battery will provide enough energy to power the exoskeleton, and a battery with an intolerably slow charging rate cannot provide the needed power to the actuators. This trade-off results in a 'safe' approach: a total energy capacity is chosen, and the size of the battery scales up or down for weight change. Battery energy efficiencies for wearable mobility systems are on the order of 67%. The worst cases occur when the battery is frequently charged and discharged. Research is ongoing to improve the efficiency, longevity, and hence usability of batteries, but significant advances for mobile applications are yet to be realized. Another approach to solving the power problem of wearables is to actually try to harness energy directly from the body as it moves through the natural environment. Present designs with an energy footprint of more than 1.5 W/kg swing foot/body mass do not maximize this potential amount of foot energy but are higher than human energy requirements. Reduced braking strategies could provide a better balance between support provided and energy generation required. Reducing braking and increasing propulsion require different exo-actuator strategies. Skin-like generators may reduce mass and maximize energy capture by covering a greater foot area [23, 24, 25].

CONCLUSION

The development of exoskeletons for mobility assistance presents significant engineering challenges, particularly in ensuring natural movement, effective control, and efficient power management. Despite the advancements in materials, sensors, and actuators, several hurdles remain, particularly in energy efficiency, system integration, and the adaptability of the exoskeleton to individual user needs. The integration of AI and real-time control systems represents a promising solution to enhance the performance of these devices, making them more adaptable to different users and conditions. As technology continues to evolve, we anticipate significant improvements in the usability, comfort, and efficiency of exoskeletons, ultimately leading to broader accessibility and better outcomes for individuals with mobility impairments. Continued interdisciplinary research and collaboration will be essential in overcoming the remaining challenges, paving the way for more effective and sustainable exoskeleton solutions.

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