Doctoral Program in Mechanical Engineering (XXXVII cycle)

Development of Methodologies, Mechatronic Solutions and Controls for Upper Body Rehabilitative Robotics

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Summary

Statistical data reveals that approximately one-sixth of the global population lives with some form of disability affecting motor abilities. In this context, robot-mediated rehabilitation can serve as a powerful tool supporting clinicians in delivering effective rehabilitative therapy.

This doctoral thesis investigates design guidelines for developing robotic rehabilitative systems that can effectively couple with physiological movement, with a particular focus on enhancing the rehabilitative potential of the Float exoskeleton.

The research addresses several aspects, beginning with exploring how different kinematic solutions can expand the device's workspace and improve its manipulability. By optimizing the exoskeleton's range of motion, the aim is to enable more effective and adaptable rehabilitation exercises.

The thesis provides a comprehensive review of the state-of-the-art in upper body rehabilitation (Chapter 2), focusing on the biomechanics of the upper limb, the effects of neurological and orthopedic impairments on the scapulohumeral complex, and the impact of neurological injuries on trunk proprioception and control. It explores current robotic rehabilitation solutions for the shoulder and trunk and evaluates control strategies used in robotic devices.

The literature analysis reveals the need for methodologies to evaluate the performance of different mechatronic designs, providing a framework of quantitative metrics to assess the potential and limitations of various solutions.

Additionally, it identifies insufficient documentation on defining actuation mechanical requirements for rehabilitative robotic systems that interface with the human body, and highlights the importance of trunk recovery during early rehabilitation stages.

In response to these identified needs, this doctoral thesis investigates whether clear metrics and methodologies can be defined to evaluate the effectiveness of different upper limb rehabilitative exoskeleton topologies in replicating human motion. It defines a subset of kinematic analysis, modelling, and simulation techniques to assess upper limb exoskeletons' ability to replicate physiological motion, which can also inform control algorithm development (Chapter 3).

Additionally, the thesis evaluates Series Elastic Actuators capable of detecting Human-Robot Interactions (HRI), offering a systematic characterization and analysis of the compliant element of the actuation mechanism. This includes mechanical evaluations through finite element analysis, frequency response, and hysteresis testing (Chapter 4).

Understanding HRI is crucial for enhancing the exoskeleton's responsiveness and safety during rehabilitation. This research examines various control paradigms to identify the most suitable strategies for achieving smooth, intuitive, and adaptive assistance that aligns with the user's physiological needs. A framework for human-in-the-loop control is proposed to enable various rehabilitation modes such as assistive, resistive, and gravity-compensated (Chapter 5).

Another key focus is exploring how the Float exoskeleton can be modified to extend its functionality beyond arm rehabilitation to support trunk movement. By addressing this broader scope, a novel prototype for trunk movement assistance is presented, extending the capabilities of the current Float passive multi-jointed arm by implementing structural redesigns and adding powered components. The goal is to transform the Float device into a comprehensive tool for upper-body rehabilitation, increasing its therapeutic versatility and ability to assist patients in recovering a wider range of motor functions (Chapter 6).

To summarize, this research contributes to robotic rehabilitation by providing (I) a methodology for assessing robotic systems' ability to mimic physiological motion, (II) a procedure to evaluate and characterize SEA sensing components, (III) control algorithms for treating impaired populations, (IV) a new approach to trunk rehabilitation. These tools establish a strong foundation for designing effective rehabilitation systems and assisting clinicians in delivering precise, high-intensity care.