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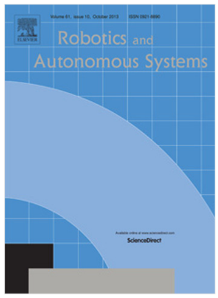

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Human-oriented Approaches for Assistive and Rehabilitation Robotics - Engineering Methods, Technical Implementation, and Treatment

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1. Introduction

Assistive and rehabilitation devices are an important emerging topic of robotics research. Various types of wearable robotic devices such as prostheses and exoskeletons [1, 2], mobile robots such as wheel chairs [3], and stationary robots such as [4, 5] have been designed and developed. All of them facilitate novel directions in supporting or augmenting users irrespective of their physical and cognitive capabilities. Despite technical advances, there are still open issues due to the limitation in technology and to the insufficient knowledge about humans [6, 7]. Since the devices incorporate and closely interact with human users, research activities and real-world applications require human-oriented approaches [8, 7]. Therefore, it seems promising to consider technical and human aspects in engineering design. Developing devices that satisfy human demands

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and fulfill technical requirements, would greatly benefit from multidisciplinary collaboration of engineering, computer science, and human sciences [9, 7].

This Special Issue gives a comprehensive and in-depth overview of current technical developments, neural and psychological background, requirement definitions, structured assessment in user studies, human-oriented design methods, and wearable robotic applications. Technically, this concerns systems engineering as well as the design of components such as control, sensors, actuators, and human-robot interfaces. To improve knowledge about the human, neural, and psychological factors are investigated. Requirement definition comprises aspects such as safety, functionality, effectiveness, and acceptance. Structured assessment of intervention effectiveness is examined in user studies. The aforementioned insights, can be exploited by methodologies that enable systematic human-oriented design processes. Finally, applications of prostheses, exoskeletons, and other wearable robots are presented.

2. Challenges and Approaches

From the global design issue described above, specific challenges can be derived. To tackle these challenges, the presented approaches combine a multitude of methods from various domains. This facilitates a holistic design and evaluation of robotic devices. The key research questions of the Special Issue and the corresponding approaches discussed in the papers are:

1. *Engineering methods:* How can biomechanical conditions and human factors be considered in a systematic fashion?
   (a) Design optimization based on simulations with a musculoskeletal model of the human body and an exoskeleton.
   (b) Human-machine-centered prosthetic design based on profound analysis and modeling of human factors.
2. *Hardware implementation:* How should structures and mechanisms be designed to enable appropriate and versatile mobility?

   (a) Effective motion support with reduced technical power requirements through elastic actuation and motion-adapted locking.
   (b) Independent mobility by a dynamically stabilized autonomous stair-climbing wheelchair with a leg mechanism.
3. *Software implementation:* Which algorithms facilitate intuitive and robust robotic assistance?
   (a) Learning sensorimotor patterns to set up adaptive motion models and design controllers to yield safe interaction with the user.
   (b) Adaptive control methods that cope with the complex dynamics of soft wearable robotic devices considering human biomechanics.
   (c) Robust human-adaptive control laws to achieve well-defined force dynamics with series elastic actuators.
4. *Interface implementation:* How can human-robot interfaces be designed to improve human performance and acceptance?
   (a) Optimization of control and feedback to customize assistance and reduce individual effort.
   (b) Shared control with varying degrees of autonomy to appropriately support users and reduce their cognitive burden.
   (c) Bimanual gesture detection for motor coordination studies based on Gaussian mixture modeling regression.
5. *Assessment:* Which methods allow for an evidence-based and holistic evaluation of user skills and intervention?
   (a) Range-of-motion assessment in robot-assisted therapy considering clinical expert knowledge.
   (b) Patient-specific, clinical assessment of the effectiveness of shoulder therapy intervention.
   (c) Supernumerary soft robotic limbs and corresponding assessment protocols for upper limb rehabilitation.
6. *Training:* Which training approaches help to individually assist users and improve their performance?

(a) Velocity-based robotic assistance to refine customized motor skill training with bio-mimetic trajectories.

(b) Robotic post-stroke training with adaptively decreasing assistance to improve motor coordination and function.

3. Guide to the Special Issue

This Special Issue gathers knowledge from disciplines like design, mechatronics, computer science, biomechanics, neuroscience, and psychology with respect to human-oriented approaches in assistive and rehabilitation robotics. It contributes to considering the human in the loop and challenges emerging from this. The articles emphasize human-oriented approaches and aim at fostering the elaboration of a systematic framework that covers human-related challenges in development and operation.

Regarding human-oriented ***engineering methods***, the question of how to systematically consider human requirements and constraints is paramount. Zhou et al. develop an approach to optimize an exoskeleton with a human body model. Physical humanexoskeleton interactions, are analyzed and evaluated considering the behavior of the human body and the exoskeleton. Beckerle et al. present a human-machine-centered approach to prosthetic design. Therefore, they suggest and perform a detailed analysis and modeling of human factors with user and expert studies. Through adjusting the human factors, the resulting method can be extended to other assistive and rehabilitation robots.

With respect to ***hardware implementation***, the contributions focus on developing task-optimized structures and mechanisms. Jimenez-Fabian et al. discuss the actuation of an ankle-foot prosthesis through a parallel spring and a variable-stiffness actuator. They show reductions of the required motor peak power, energy, and especially torque. Similarly, Cherelle et al. report distinctly lower power requirements when using an elastically-acutated prosthetic foot with a locking mechanism. Going beyond prosthetic application, Hinderer et al. point out the importance of mobility for wheelchair users. They introduce an autonomous stair-climbing wheelchair based on a leg mechanism as an alternative to caterpillar-based ones. With this kinematic solutions, the system provides secure and adaptable stair climbing.

Software implementation is of high relevance when it comes to designing intuitive and robust robotic assistance. Pignat et al. present a learning algorithm that adapts robotic dressing support to different user morphologies, preferences, and requirements. Learning from sensory information and motor commands, it allows to react to different users characteristics with minimal intervention. Khanh Dinh et al. show an approach to reach kinematic transparency by an adaptive control. Taking into account transmission-intrinsic non-linear friction and backlash hysteresis, it enables robust force-support of users wearing an upper limb exosuit. For elastically-actuated devices, Calanca et al. analyze the impact of human dynamics on the widely-adopted method of impedance control. Despite physical human-robot interaction can result in inaccurate impedance rendering with common approaches, their human-adaptive force controller guarantees predictable performance.

Interface implementation is highly promising from the users point of view and the engineering perspective since it can improve human performance and acceptance. Yoon et al. design an assistive human-robot interface with user-specific haptic and visual feedback. To improve task performance, users' control strategies are modeled in terms of inverse optimal control. The work of Erdogan & Argall focusses on the users' cognitive loading when sharing control with the robotic device that assists them. A comparative study of four methods indicates that autonomy can reduce user effort while its utilization is differing between the control paradigms, but not the interfaces. Since no single paradigm is clearly superior, they suggest to offer end-users multiple control options. Shah et al. focus on bimanual gesture recognition and analyze potentials and current limitations. Moreover, they suggest a detection algorithm that accurately tracks both hands without constraining them physically.

Evidence-based and holistic ***assessment*** is required to evaluate the clinical outcome of interventions. For range-of-motion measurement in robot-assisted ankle-foot rehabilitation, Chen et al. suggest a therapist-joined method. They combine therapist-joined zero torque control and proxy-based sliding mode control and achieve improved measurement accuracy. Varela et al. assess the effectiveness of shoulder therapy with a system measuring upper limb movements. It is used in a clinical study and delivers data for designing patient-tailored robotic exoskeletons. The Soft-SixthFinger of Hussain et al. assists patients during paretic upper limb rehabilitation. Besides assisting users, it serves as a motivation tool to perform task-oriented rehabilitation activities. A pilot study with standard rehabilitation tests indicates that the patient was enabled to perform previously impossible tasks.

Training is essential to help individual users to exploit their robotic aid. The velocity-based assistance scheme of Tanaka supports motor learning/training by bio-mimetic trajectory generation. For training, the time scale of the reference profile is automatically adapted to individual levels of task-related motor skills from previous trials without assistance. A pilot study shows that the reference profile can be regenerated with minimum jerk and that the procedure facilitates the acquisition of task-related motor skills with a reduced number of trials and temporal errors. The training scheme of Marini et al. relies on compliant patient and robot motion as well as online modulation of assistance. In user experiments, improvements regarding upper extremity spasticity, motor functions, and range of motion are observed while adaptively decreasing assistance.

4. Outlooks

The articles in this Special Issue highlight the importance of human-related challenges in assistive and rehabilitation robotics. Robotic devices need to adapt to their users and assessment/training designs are required to comply with the robotic devices. Moreover, psychological and physiological aspects in design, control, and therapy should be considered to achieve effective human-robot interaction and treatment. Systematic methods for this purpose are scarce and need further research.

Technically, elastic actuation and intelligent kinematic and locking mechanisms are promising in terms of actuation. Beyond such hardware aspects, software needs to be designed to user preferences and characteristics. Ideally, this should be implemented in a transparent fashion with minimal intervention, and predictable behavior. On the contrary, a certain autonomy of the robotic devices can reduce the cognitive effort of the users. An appropriate compromise still needs to be found as shown by the papers.

For treatment, robotic devices are promising tools for measurement and as a motivation for the patients. Task-oriented rehabilitation techniques appear to be most promising and technical research might be combined with clinical metrics. Thereby, it is key to consider the individual capabilities of the users/patients and to adapt online if required.

In conclusion, the field of assistive and rehabilitation robotics shows various potential for future research on human-oriented methods. This Special Issue gives and overview to current developments and thereby an outlook to how the field might develop in the future.

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