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Critical validation of design strategies for a compact upper limb mechatronics rehabilitation device

Tomislav Bazina[1], Saša Zelenika[1], Ervin Kamenar[1] and Tea Schnurrer Luke Vrbanić[2]

[1]University of Rijeka, Faculty of Engineering & Centre for Micro- and Nanosciences and Technologies, Vukovarska 58, 51000 Rijeka, CROATIA
[2]University of Rijeka, School of Medicine & Clinical Hospital Centre, Braće Branchetta 20, 51000 Rijeka, CROATIA

sasa.zelenika@riteh.hr

Abstract
Traditional physical rehabilitation therapy, aimed at recovering upper limbs' functionality of stroke patients, still mainly relies on the assistance of therapists. Mechatronics-based rehabilitation devices enable, in turn, a large number of automated high-intensity movements, thus assuring a more effective rehabilitation with fewer resources. Some commercial solutions of this type are available, but they are generally expensive, heavy and voluminous, while not allowing the power contribution to be adjusted to the autonomous effort provided by the patients, as well as having a very uneven number and distribution of the used degrees of freedom (DOFs). The aim of this work is to provide a critical assessment of the needed number of active and passive DOFs as well as of the viable control approaches to obtain the needed functionality of the device. The resulting solution should be as simple as possible, while allowing to achieve rehabilitation efficiency by improving patients' upper limb coordination and ranges of motion of each joint.

Upper limb rehabilitation, compact mechatronics device, design analysis, DOFs, adaptive control

1. Introduction

Stroke, a frequently occurring medical condition, is a major cause of impaired arm movements. Conventional rehabilitation methods imply time-intensive procedures performed by the therapists. Due to the inherent limitations, a different approach is necessary to improve rehabilitation efficiency. A promising approach is the development of active mechatronics-based rehabilitation devices [1]. Novel devices, with marked advantages with respect to conventional therapy, are hence being developed, but the commercially available ones are generally expensive, heavy and voluminous, with several shortcomings and a far-from-standardised and far from optimal distribution of the used degrees-of-freedom (DOFs) [2-3]. The aim of this work is to provide a preliminary design analysis for the development of a compact upper limb rehabilitation device. Different design paradigms, implying compactness, portability, limited weight, low cost, accessibility and user-friendliness are taken into account. Recent design strategies are compared, while considering also the used interfaces of the devices and the patients as well as the perspective control typologies.

2. Rehabilitation device design goals

An essential first step in designing a rehabilitation device is a thorough study of human arm kinematics. Due to its complexity, especially for the shoulder, attempts to design devices that would exactly replicate arm's kinematics are hardly feasible, and result in kinematic incompatibility, limited ranges of motion (ROMs), non-smooth interactions, lengthy dress-on/dress-off times, uncontrollable forces and deformations of patients' skin [4]. Alignment-free [5] and self-aligning [6] designs, characterized by parallel connections to human joints, have thus been suggested. Such design approaches allow misalignment compensation between the rehabilitation device and the human arm via additional passive DOFs. To facilitate the usability and rehabilitation efficiency, in terms of improving patients' arm coordination and joints' ranges of motion, a suitable number of active and passive DOFs should therefore be provided, which constitutes the primary design objective. The resulting rehabilitation device should also provide redundant and fail-safe safety features, and a coupled robust and user-friendly control system. This should be complemented by the possibility to provide high-intensity dynamic interactions, compactness, and low cost.

2.1. Consideration on the necessary DOFs

Based on the above considerations, the number and spatial arrangement of the DOFs of the rehabilitation device are the main concerns in its design. Different design perspectives result, in fact, in various DOFs distribution across the shoulder-elbow-wrist-hand interaction chain. A thorough analysis of design configurations described so far in available literature is thus performed. The summary of the recent and most promising rehabilitation systems, with respect to the corresponding interactions with human arms, is hence provided in Table 1. Although active systems [7] have the advantage of providing highly dynamic interactions, in conjunction with a high control bandwidth and, in some instances, are already used in hospitals [4], in general they comprise only revolute joints and allow rehabilitation in limited ROMs. To extend the workspace, often the number of active DOFs is thus increased, resulting in bulky constructions. In order to minimize the number of active DOFs and increase the ROMs, the mentioned self-aligning design configuration [6] incorporates, thus, two additional prismatic joints aimed at shoulder misalignment compensation. The alignment-free configuration [5] comprises, in turn, one prismatic shoulder joint. For elbow misalignment compensation, both configurations use an additional passive prismatic joint.

Based on the performed analyses, a design based on a self-aligning configuration with one active revolute joint (r_A) for the hand interaction, two r_A joints, one prismatic passive (p_P) and one spherical passive joint (s_P) for the wrist, two r_A and one p_P joints for the elbow, as well as three r_A and three p_P joints for the shoulder interaction is deemed necessary. The thus proposed device configuration, comprising eight active and six passive joints, is hence depicted in Figure 1.

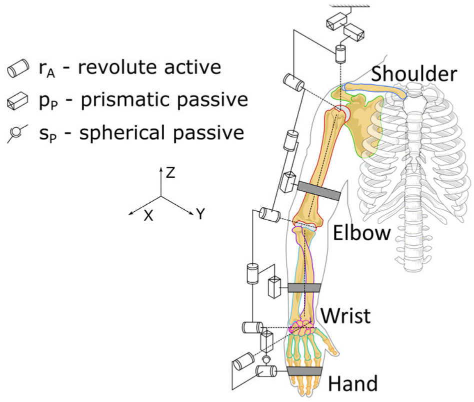

Figure 1. Scheme of the proposed rehabilitation device configuration.

2.2. Issues in controlling the upper-limb rehabilitation device

Three different approaches could be followed to achieve the control of the foreseen rehabilitation device. In a first instance, it could be controlled so that it replicates therapists' actions in assisting the patients while performing certain movements. A commonly used approach is, in turn, to allow the therapist(s) to subjectively adjust, for a determined patient, the needed level of assistance that the active device provides. The third, and the most challenging approach, that is aimed for in the herein considered work, is to adaptively tune the extent of assistance based on real-time measurements of patients' motion ability [4].

The first two approaches are generally based on a position feedback loop, combined with feed-forward blocks that allow compensating the known disturbances (friction forces, inertias and mases). On the other hand, if the third approach is followed, control algorithms, coupled with sensors, should provide the capacity for the device to "hide" its activity to the user (transparency) and to tune the level of provided assistance (adaptability), while keeping, by imposing joint constraints or generating reactive forces, patients' trajectories close to nominal paths [4, 7]. Transparency and adaptability make the control even more complex, since the rehabilitation device should provide in this case only the minimal assistance needed to perform the movements, while allowing dynamic adaptability to patients' active participation. Proper therapy is hence assured and patients' compensatory strategies, which diminish inter-joint coordination, are minimized. In this case, however, the position feedback is not sufficient, but the control relies on sensing patient's intentions as well as the level of motion ability. A commonly used technique to acquire the thus needed data is to use electromyography (EMG) sensors, allowing a non-invasive estimate of muscles' tensions. The main drawback of this method is, in turn, poor signal-to-noise ratio (SNR) and the cross talk between different muscles, so that the effective positioning of the sensing electrodes is crucial [4]. More recently, the usage of inertial measurement units is thus suggested [8].

3. Conclusions and outlook

A preliminary analysis of possible design configurations of an upper limb rehabilitation device, based on common design practices, is provided in this work. Several design goals are considered from the perspective of usability, safety and utility, while existing active rehabilitation devices with self-aligning concepts are considered so as to establish design guidelines for the development of a user-friendly, portable, lightweight and low-cost device. Special emphasis is on patient-device interactions, redundancy and the number and placements of the DOFs needed to enable smooth therapy sessions, and an efficient recovery of patient sensory and motion capabilities.

Different means of rehabilitation device control, together with the required sensing and actuation elements needed to adapt the level of assistance to patients' needs, are also considered.

Future work will include modelling the rehabilitation device in an adequate CAD environment, performing a thorough study of the kinematics and the respective ROMs, and performing structural and kinematics optimization with inclusion of compliant passive elements. A selection of the required sensors and electric actuators, as well as of the suitable data acquisition and control hardware and software, will also be done.

It is foreseen that the modelling of the resulting nonlinear system will be performed by using a data-driven machine learning approach based on Koopman operator theory, which allows an accurate linear representation of a nonlinear system by lifting its nonlinear dynamics into a higher dimensional space [9]. This should allow obtaining a data-driven state-space model representation of the developed rehabilitation device, as well as the development of simpler yet more powerful and, possibly, predictive control module(s).

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Table 1. DOFs distribution in self-aligning, alignment-free and design configurations without passive DOFs.

Configuration		Self-aligning			Alignment-free			Systems w/o passive DOFs								
		SAEM [6]			X-Arm-2 [5]			ANYexo [7]			ARAMIS [3]			ARMin V [2]		
Actuator type		-			Brushed DC			Elastic actuators			Brushed DC			Brushed DC		
Max torque / Nm		-			19.3			55			94			> 38.5		
Max speed / $°\cdot s^{-1}$		-			-			173			-			178		
Interaction		A	P	Σ	A	P	Σ	A	P	Σ	A	P	Σ	A	P	Σ
DOFs	Shoulder	3r	2r 2p	7	3r 1p	2r	6	5r	-	5	4r	-	4	3r	-	3
	Elbow	1r	3r 1p	5	2r	1p	3	1r	-	1	2r	-	2	2r	-	2
	Wrist	-	-	0	2r	3r	5	-	-	0	-	-	0	1r	-	1
	Hand	-	-	0	-	-	0	-	-	0	-	-	0	1r	-	1

Number of DOFs: A: active, P: passive, Σ: overall number. Type of joints: r, revolute; p, prismatic; s, spherical.