TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 64, Issue III, September, 2021

CardioVR-ReTone – 14 DOFs UPPER-BODY ROBOTIC EXOSKELETON DESIGNED TO SUPPORT CARDIAC REHABILITATION

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Abstract: *Cardiac rehabilitation following a cardiac surgery involves delivery of structured exercise, training, and psychological support, in a cost-effective manner. Most of these rehabilitation strategies need sessions of motor recovery to improve joint range of motion, fortify muscles, restore cardiac functional capabilities, and resolve impairments of the patient upper body. For this reason, within this paper, we design a new structure of upper limb exoskeleton augmented by a Virtual Reality (VR) platform with the following novel features: new shoulder girdle mechanism for driving the necessary actions of the shoulder mechanism throughout its range, without soreness for the patients; to match with the anatomical structure for minimizing unwanted remaining force to the human joints; and integration of the robotic exoskeleton and VR system in one system.*
Key words: *Cardiac rehabilitation, robotic exoskeleton,*

1. INTRODUCTION

Cardiac rehabilitation (CR) involves delivery of specific structured exercise, and education in a cost-effective manner. Robust evidence demonstrates that cardiac rehabilitation, done correctly, reduces mortality up to 25%, improves functional capacity, and decreases re-hospitalization [1,2]. An appropriate rehabilitation is essential for enabling those people to live independently and enhance their Quality of Life (QoL) as they age. Most of these rehabilitation treatments need sessions of motor therapy to improve joint range of motion, fortify muscles, restore cardiac functional capabilities, and resolve impairments [3, 4]. To be effective in terms of time, a CR therapy after an open cardiac surgery should take between 2 and 6 weeks partly in hospital, partly at home [5,6,7]. The continuity of care is often interrupted in the hospital-to-home transition due to the limited number of qualified human therapists who can provide this treatment, while the demand is growing, particularly as population is aging. Another disturbing aspect is that the patients tend to get tired and consider the rehabilitation process monotonous, as time goes by, which often end up by losing motivation for rehabilitation [8]. In compliance with to [6, 9] the cost of rehabilitation therapies rises worldwide from year to year. For example, in Denmark in 2018, motor rehabilitation therapy throughout 3 weeks following heart valve surgery exceeded 20.000 € per patient [6].

Because of these high costs, most of the patients lack the opportunity of adequate CR therapy. While there remain a few procedures that only human therapists can do, many rehabilitation exercises are highly repetitive [10, 11]. This is where robotic systems outperform the humans. They can perform the same task(s) with high precision and without exhaustion or loss of attention and concentration [12]. Still, the addressability of such robotic exoskeleton systems in delivering therapy after a cardiac open surgery or a major cardiac event is very limited [13-15]. The use of digital therapeutic games and Virtual Reality (VR) platforms coupled with Artificial Intelligent agents in rehabilitation practices are increasing [17].

Thus, the interest in developing new robotic devices for medical rehabilitation is due to their

Received: 30.07.21; **Similarities**: 09.08.21: **Reviewed**: 01.09./20.0821: **Accepted**:15.09.21

capacity to perform repetitive tasks and because they allow to evaluate the patient progress objectively [18, 19].

Within this paper, we introduce CardioVR-ReTone, an upper body robotic exoskeleton with a functional shoulder structure that ensures regular mobility all around the shoulder with a normal range of motion (ROM) and standard actuators which allows good control of impedance and force. In the next paper sections, we present the mechanical design, electrical and control strategy, the VR module, and the overall design of the CardioVR-ReTone.

2. Theoretical background and methodology

In this section, the most important aspects of the exoskeleton design will be highlighted. The human upper body biomechanical parameters (anthropomorphic measures and movements) are identified to estimate the required torque for providing the expected ROM, the actuators sizing, and the constrains are also considered.

2.1. Anatomy of the Upper Limbs

The human upper limb comprises primarily of the wrist, elbow, and shoulder complex/ joints.

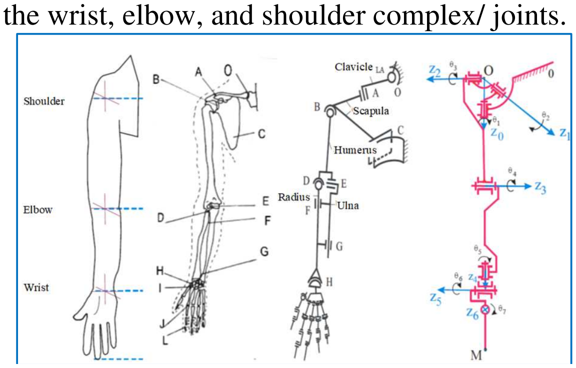


Fig. 1. Structure of the human upper arm and biomechanism of the upper arm [adapted from 13].

The *shoulder joint* of a human shown in Fig. 1 consists of three bones: the humerus (the upper bone of the arm), the scapula, and the clavicle, as well as the associated tendons, ligaments, and muscles. The large shoulder joint is the glenohumeral joint, which is generally referred to as the "shoulder joint". The joint of shoulder contains the part of the body where it attaches to the humerus and scapula.

To allow a wide range of arm and hand action the shoulder must be mobile enough, but also stable enough to allow lifting, pushing, and pressing [20, 21].

Basically, the complex of the shoulder can be shaped like a ball joint. In addition, the position of shoulder joint rotation center position changes with the movements of the upper arm.

The *elbow complex* highlighted in Fig. 1, consist of elbow joint and radio-ulnar joints [23]. The proximal radio-ulnar joint, the humero-radial joint and the humero-ulnar joint constitute the elbow joint. All three cavities formed communicate with each other because the capsule is common. Overall, the elbow joint complex accepts 2 DoF, flexion and extension, pronation - supination.

The *wrist* is a complex joint that connects the bones of the forearm to those of the hand. The CardioVR-ReTone will not address the rehabilitation of the patient's wrist - consequently the wrist will not be anatomically detailed.

Table 1

Body size by country [15].

	Male			Female		
Country	**Average height [m]**	**Weight [kg]**	**BMI**	**Average height [m]**	**Weight [kg]**	**BMI**
Romania	1.77	85.1	27.1	1.64	72.2	26.8

Table 2

Mass of the human body segments [16].

Body segment	Female [%]	Male [%]	Mean [%]
Forearm and hand	2,07	2,52	2,295
Hand	0,5	0,65	0,575
Forearm	1,57	1,87	1,72
Upper arm	2,9	3,25	3,075
The whole arm	4,97	5,7	5,335

The wrist joint has 2 DoF: flexion and extension and deviation of the radial/ulnar. Wrist movements are produced around an instant center of rotation. Regarding anthropomorphic parameters of the human body, table 1 shows the body size for people from Romania [15]. Table 2 shows the mass of the numerous segments of the human body, as a percentage of the total weight, for people from Romania (see Table 1).

2.2. Biomechanics of the Upper Limbs

The scapula, shoulder, forearm, and hand motion characterize the kinematics of the upper limb (Table 3). Generally, by performing individual movements or as a combination of two or more movements, these components of the arm are responsible for positioning the hand in the Cartesian space. Each component involved in arm kinematics has minimum 1 DoF with a limited ROM, as shown in Table 3. The motions involved in placing the hands in the Cartesian space are flexion/ extension of the scapula; shoulder flexion/ extension, adduction/ abduction, median/ lateral rotation; elbow flexion/ extension; pronation/ supination of the forearm, abduction/ adduction and flexion/ extension of the hand.

Table 3

Upper limb elements and range of motion [8].

	DoF	Rotation angle upper limit / lower limit (degrees)	Movements
Elbow	1	10/150	Extension / Flexion
Wrist	1	30-40/25-30	Adduction / Abduction
	2	60-90/60-80	Extension / Flexion
Forearm	1	80/90	Supination / Pronation
Shoulder	1	60/140-180	Extension / Flexion
	2	20/90	Lateral / Medial
	3	20/180	Adduction / Abduction
Scapula	1	15/20	Extension / Flexion

Therefore, the human arm kinematics, in a fixed position, can be defined as a system with 7 DoF: 3 DoF for the shoulder, 2 DoF for the elbow, 2 DoF for the wrist.

But when you consider the fact that the moving shoulder changes its center of rotation position, then the complexity of the shoulder mechanism increased and the necessary number of degrees of freedom also increases.

2.3. Design specifications for the CardioVR-ReTone exoskeleton

Identifying the requirements (stakeholders needs, technical and safety requirements, other requirements) for a robotic upper limb exoskeleton dedicated to cardiac patient rehabilitation will be a rather difficult process as there is little research in the field. Because the mechanical part of the robotic exoskeleton interacts directly with the patients, most requirements are functional, and thus difficult to translate into mathematically verifiable answers. To identify the functionalities of the robotic exoskeleton, a focus group was created composed by 3 design engineers, 3 robotic engineers, 4 cardiologists, 2 surgeon cardiologists, 4 cardiac patients (>65 years), and 3 young volunteers (>22 years).

The starting point in identifying the functional requirements for the robotic exoskeleton was the need of upper body movements for cardiac rehabilitation. The arm movements necessary for cardiac rehabilitation after open cardiac surgery are highlighted in figure 2 [12, 22].

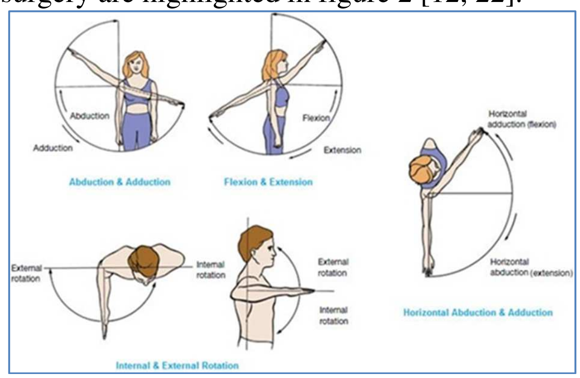


Fig. 2. The arm movements necessary for cardiac rehabilitation after open cardiac surgery [12, 22].

The desired functionalities of the CardioVR-ReTone exoskeleton will be highlighted and a set of performance requirements will be formulated that will support the requested functionalities.

To be attractive and to facilitate the exercise the exoskeleton will be augmented with a non-immersive VR module. Thus, the CardioVR-ReTone exoskeleton will help the user in his movements, transferring part of the muscle load to the exoskeleton load, in a safe way. Therefore, the ROM of the CardioVR-ReTone exoskeleton should not extend beyond the ROM of the upper limbs of a human user (patient). Ideally, the CardioVR-ReTone exoskeleton should be able to function in the full range of human arm movements.

The following list contains the functional requirements of the CardioVR-ReTone exoskeleton, identified by the focus group:

- The CardioVR-ReTone exoskeleton must accurately follow the movement of the cardiac patients' arms during the imposed exercises and must have the following behavior:
  - to support cardiac patients when they are unable to perform the selected recovery exercise (*full-assist mode*).
  - not impose additional resistance to the arms movement - when they are performing the selected recovery exercise (*assist mode*).
  - to impose additional resistance to the arms movement - when they are performing the selected recovery exercise (*active-assist mode*)
- The CardioVR-ReTone exoskeleton must be safe in operation and not injure the user by forcing the joints into positions that are not permitted by normal human movement and motor behavour.

2.4. Exoskeleton Mechanical Design

The steps to design the CardioVR-ReTone robotic exoskeleton for upper body were as follows:

- Identifying the needed rehabilitation movements for the upper body of cardiac patients.
- Sizing and selection the actuators together with the reducers. The necessary sensors are also carried out – ex. position sensors, and EMG sensors.
- Design the mechanical structure based on anthropomorphic characteristics while considering the comfortability for the cardiac rehabilitation process.
- Decide the control strategy and design the control system for the exoskeleton.

The structure of the exoskeleton is built by seven mobile parts or links on each arm displayed in figure 3. So, The CardioVR-ReTone exoskeleton has fourteenth degrees of freedoms in total. The first five motors represent the shoulder joint, and the six motor and seventh passive joint represent the elbow joint (Fig. 3.).
The upper arm normal movements of a human are firmly coordinated with the shoulder girdle movements, characterized by the scapula-humeral "tempo". To achieve the upper-body movements full range, the shoulder girdle and the upper arm must be actuated synergistically. Without awareness to the synchronized movement of the shoulder, joint instability may occur, and pain or injuries may result in shoulder (ex. medical illness of the rotator cuff and irritation) [9].

a) Left view.

b) Right view.

Fig. 3. Virtual prototype of the CardioVR-ReTone exoskeleton (3D model).

The lack of connection with the upper arm of the patient makes the exoskeleton less responsive to the kinematic inconsistency nearby the shoulder. The ***shoulder mechanism*** was designed as a rotation joint. The rotation joint, J1, will duplicate the raising and lowering the shoulder mobility, and the triangle J2-J3-J4 (Fig. 4), replicates the shoulder protraction and retraction mobility. Arranging the joints in a triangle solves the kinematic inconsistency that would be created if for the protraction and retraction at the rear side of the shoulder only one rotation joint would have been used.

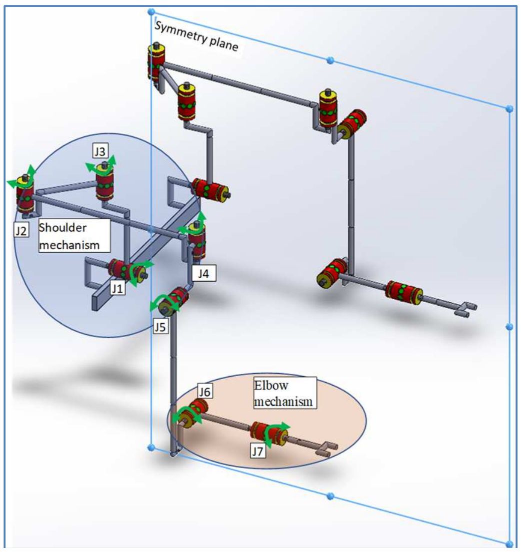


Fig. 4. Schematic view of the CardioVR-ReTone exoskeleton - shoulder mechanism combined with the elbow mechanism.

The ***forearm mechanism*** was designed as two revolute joints positioned at an angle of 90º. This solution was adopted for forearm mechanism to improve the ROM while preventing mechanical singularities and undesired movements obstructions of the upper arm. Joint J4 is aligned to the vertical cartesian axis, while axis J5 is aligned to the axis X (Fig. 4).

The ***elbow mechanism*** was designed as two revolute joints, one is active actuated by a motor (Fig. 4 – J6) and facilitate the flexion – extension of the elbow and the other one is passive (Fig. 5), without being actuated by a motor, facilitating the independent rotation of the forearm - elbow internal rotation – external rotation. The passive joint of the elbow mechanism, joint seven (Fig. 4 – J7), is realized as a circular mechanism – "circular bearing" (Fig. 5); such a solution is both free of singularity and not too invasive. The first joint of the elbow is driven by a Maxon motor attached to the linkage element from the shoulder mechanism.

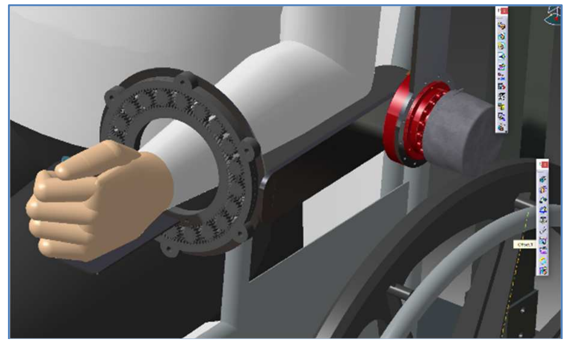


Fig. 5. Virtual prototype of the elbow mechanism (3D model).

The CardioVR-ReTone exoskeleton has two robotic arms, one for each human arm (Fig. 3). These two robotic arms of the CardioVR-ReTone exoskeleton are mounted on an adjustable frame (height- and width-) that makes it adaptable to various human dimensions.

Thus, the resulted design is a simple, integrated and morphologically compatible exoskeleton combined with a distributed actuators mass and volume along the robotic exoskeleton structure.

The movements that the exoskeleton can make together with the upper body and arms are: abduction & adduction; flexion & extension; horizontal abduction & adduction; internal & external rotation.

2.5. Actuation system

Robotic exoskeletons provide therapeutic trainings for rehabilitation based on force- or impedance-, such as resistant maneuvers based on impedance and trainings based on force. To deploy various therapeutic exercises based on force- and impedance we selected Maxon motors, because a Maxon provide precise and stable force control with sturdiness to impulsive disturbances and can produce a low impedance, which is important to promote patients' intended actions.

According to [15] and having in mind the information from the Tables 1, 2, 3, the mass of the upper arm and the lower for a medium-sized person in Romania, are 2.97 kg, respectively 2.3 kg. Also, the lengths of the upper and lower arms are almost 40 and 45 cm. To be able to generate all the shoulder and elbow movements, the CardioVR-ReTone, have 7 DoF on each arm (Fig. 3, 4, 5).

To calculate the required torque for choosing the necessary motors (*by motor we mean during this paper the tandem motor-reducer*) the mathematical formalism highlighted on [24] for “arm application”, was used. Thus, in worst scenario when the exoskeleton motors must carry the weight of patient’s arms and exoskeleton’s parts, highest required torque for shoulder motors are J1=134.68 Nm; J2=106.14 Nm, J3= 101.2 Nm, J4=69.74 Nm, J5=42.01 Nm, and respectively elbow motor is J6=7.10 Nm.

2.6. Operation and control architecture

In terms of how the CardioVR-ReTone robotic exoskeleton will work and how it will be controlled, the idea we want to implement is that the healthy subjects will "train" the system, "learning" (recording) the movements to be made and thus forming "references". Based on these "references" will then support patients in performing rehabilitation movements/exercises. The system will determine the level of exercises execution compliance and will be able to adapt the VR output according to this level. Using gamification mechanisms, the VR output (a 3D "game") will follow the extrinsic motivation of the patient to perform the exercises correctly and at the tempo suggested by the physiotherapist. Architectural diagram of CardioVR-ReTone software module is presented in figure 6. The constructive logical blocks of the CardioVR-ReTone software module, as well as the interdependencies between them, are represented in Table 4, respectively in figure 5.

In principle, the architecture follows a distributed control model and a blackboard design pattern. Two user roles are considered: (1) the patient in need of rehabilitation and (2) the fit user (“healthy”), who performs the rehabilitation movements to set a “reference” of the correct execution of the exercises.

The sensors and actuators (hardware elements) are controlled, at a logical level, by the sensor and actuator modules ("drivers" of the hardware components). These driver modules communicate with the other modules through messages transmitted on specific (topical) communication channels, through an asynchronous communication mechanism, coordinated by the communication module.

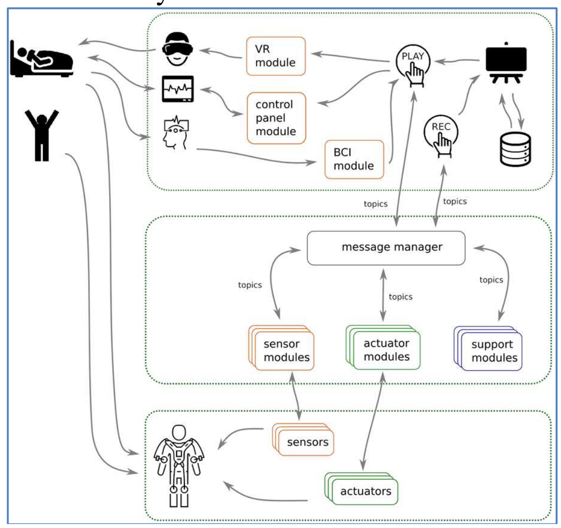
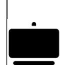
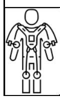


Fig. 6. CardioVR-ReTone architectural diagram - the constructive logical blocks of the operation application

Table 4

Logical blocks of the operation application of the CardioVR-ReTone system.

	Patient interacting with CardioVR-ReTone exoskeleton for post-surgery recovery (main user role)
	Healthy user, who interacts with CardioVR-ReTone to perform recovery sessions consisting of specific exercises to "learn" the system (and thus obtain the reference "exercises performed properly")
	VR system, through which the patient performing the recovery movements visualizes the 3D game “companion”
	Operation panel (control/ setup) of the application; can run on a standalone display, tablet-pc, other mobile device
	Brain-Computer Interface (BCI) through which we aim at (a) interpreting the patient's state of comfort during the execution of exercises and (b) determining correlations between his brain activity, the level of comfort during training and the level of correctness of the execution of exercises
	Blackbox mode, to manage objects that model rehabilitation exercise sets and associated meta-data; this module also has the role of interpreting the “records” of the exercises performed by the healthy users and converting them into solutions/“references”

	(models through which we classify the types of rehabilitation exercises)
	The module that ensures the persistence of information
	The module that "records" the rehabilitation exercises performed by the healthy user
	The module that "plays" a set of rehabilitation exercises, supporting the patient in their execution, monitoring their performance, and displaying the 3D VR game that accompanies the execution of the exercises
	CardioVR-ReTone robotic exoskeleton

Support modules are software modules containing business-logical functions (without hardware component) necessary for the operation and control of the Cardio-VR system.
The BCI module takes the signals from a BCI sensor (BCI headphones), classifies them, and transmits them to the play module, so that it can correlate them with the execution of rehabilitation exercises. The control panel module coordinates the display through which the system is started / stopped / configured (by the user or by the physiotherapist). The VR module plays the 3D game to the patient, during the rehabilitation exercise session, receiving the input parameters from the "play" module. The VR module will be detailed, in terms of technology, in the next paragraph.
The **Virtual Reality** module used in the CardioVR-ReTone system has as main element the virtual reality headset, which allows the user to perform his rehabilitation exercise session in the form of a "game". In this game, different scenarios will be created that allow him to configure personalized exercises according to the needs of each patient. The virtual reality application is to be used to monitor the user's progress and provide them with a detailed perspective on their progress during the rehabilitation exercise session.
Virtual reality system controllers can also be used to give the user more control in the virtual reality environment, or only the headset can be used to display the patient's digital rehabilitation scenario. The interface of the VR environment being synchronized with the exoskeleton in order to follow the user's progress in the real environment and to translate this progress into the digital environment within the virtual reality environment interface.

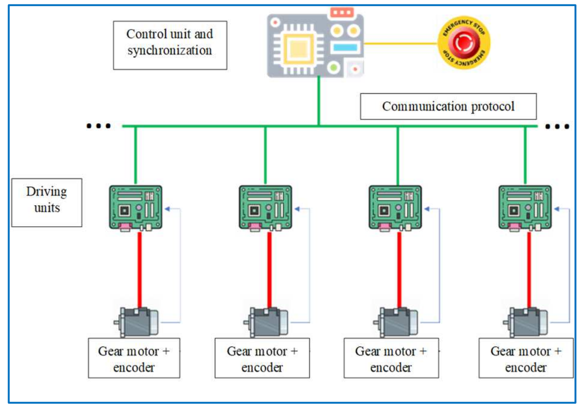


Fig. 7. The architecture for controlling and operating CardioVR-ReTone robotic exoskeleton.

Going deeply into the control architecture of the CardioVR-ReTone exoskeleton one can detail the following main components (Fig. 7):
• *Actuators* - composed of the motor-reducer assembly and encoder type position, speed, and acceleration feedback element. The power supply to the actuator and the feedback element is connected to the control unit.
• *Control unit* - which has the role of performing the positioning process by driving the actuator to the position required by the control unit with certain performance parameters like speed, torque, etc.
• *Control and synchronization unit* - which connects to the VR elements and contains the control algorithm that provides the coordinates of coordinated movement of the actuators to obtain the template specific to the selected recovery exercise. In addition, control elements can be connected to the control unit to trigger certain specifications. The control elements must be available to the person performing the recovery exercises.
• *Emergency stop* - must activate the Safe Torque Off functionality and stop the exoskeleton drive system urgently. During preliminary and running tests, when control errors could occur, motors operating the robotic Cardio-VR-ReTone exoskeleton may generate unwanted violent movements. Because some errors are only observed for the first time when the first prototype tests are performed, the

implementation of the emergency stop function is a mandatory step to avoid injuring the patients and damaging the exoskeleton mechanics. The emergency stop function is also required by the collaborative robot's technical specification ISO/TS 15066 [25].

3. CONCLUSIONS AND DISCUSSIONS

The effort presented in this paper was to design an exoskeleton – identify the stakeholders needs, select the actuation type, realize 3D model, establish the control strategy and contouring the VR application that will augment the exoskeleton - called CardioVR-ReTone, for upper-body rehabilitation of cardiac patients. The intention regarding the CardioVR-ReTone exoskeleton is to achieve advanced kinematic and dynamic attributes for helping the rehabilitation of cardiac patients.

In many previous works regarding robotic exoskeleton designs for upper body, the shoulder mobility was simplified due to the mechanical, actuating and control complexity, resulting in a reduced number of joints/DoFs of the exoskeleton. Also, the assessment of the kinematic compatibility between the interaction of the exoskeleton with the upper body has not often been reported in the scientific literature. To overpass these issues, we have designed a shoulder complex for the CardioVR-ReTone exoskeleton that describes and allows all anatomic shoulder movements, that are necessary for the cardiac patients' rehabilitation. In addition, the control strategy can actively support and dynamically sustain the rehabilitation process, and the VR platform augment and motivate the patient to continue and to complete their exercises. The kinematic compatibility of the shoulder complex was empirically evaluated by making a simulation in Catia using the humanoid model and evaluate the behaviour of the exoskeleton during the synchronized motions of the shoulder. The validation of the kinematic and dynamic model for the CardioVR-ReTone exoskeleton will be made by using the Denavit–Hartenberg mathematical formalism and will be highlighted into a future paper.

Since the CardioVR-ReTone exoskeleton is designed to operate with independent control on each axis / joint, the system will be able to be programmed to function as *full-assist mode*, *assist mode*, and *active-assist mode*. Moreover, the way of independent control of each axis allows keeping track of the movements of each joint during performing the rehabilitation exercise. This feature will help monitor the rehabilitation process and allow the physiotherapist to accurately analyse the trajectories of the arms while performing specific tasks, such as lifting or moving the arms apart. This will also be helpful to analyse the movement correctness of each path of the joints. This approach will make it possible to determine the relevance of using the exoskeleton when taking over the entire task of the movement in active-assistive and passive mode and to create a database with "references" and real data and using gamification mechanisms to improve future personalized rehabilitation strategies.

However, some design work is still undergoing regarding the optimization of the shoulder and elbow complex. The prototype of CardioVR-ReTone is expected to be constructed at the end of 2021. The exoskeleton will be than tested on volunteers, and based on the feedback from the volunteers, a series of adjustments will be made, after which it will be tested on cardiac patients.

ACKNOWLEDGEMENT

This work was supported by a grant of the Romanian Ministry of Education and Research, CCCDI - UEFISCDI, project number PN III-P2-2.1-PED-2019-1057, within PNCDI III.

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CardioVR-ReTone - EXOSCHELET ROBOTIC CU 14 GDL PENTRU PARTEA SUPERIOARA A CORPULUI DESTINAT REABILITĂRII MOTORII A PACIENȚILOR CARDIACI

Reabilitarea cardiacă după o intervenție chirurgicală pe cord deschis implică realizarea de exerciții fizice structurate, educația și reducerea riscurilor cardiace, într-un mod sustenabil. Majoritatea acestor strategii de reabilitare au nevoie de sesiuni de recuperare motorie pentru a îmbunătăți amploarea mișcării articulare, pentru a întări mușchii, pentru a restabili capacitățile funcționale cardiace și pentru a rezolva deficiențele pacientului. Din acest motiv, în cadrul acestei lucrări, vom proiecta o nouă structură de exoschelet pentru membrele superioare ale corpului uman augmentat de un sistem de Realitate Virtuală (VR) cu următoarele caracteristici noi: mecanism nou pentru complexul umăr care să faciliteze realizarea mișcărilor necesare ale brațelor fără disconfort pentru utilizator și care să se potrivească cu structura anatomică a omului și care să minimizeze forțele reziduale nedorite din articulațiile umane; integrarea exoscheletului robotizat și a modulului de VR într-un singur sistem.

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