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Design and Kinematic Analysis of a Novel Upper Limb Exoskeleton for Rehabilitation of Stroke Patients

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Abstract— **This paper details the design process and features of a novel upper limb rehabilitation exoskeleton named CLEVER (Compact, Low-weight, Ergonomic, Virtual/Augmented Reality Enhanced Rehabilitation) ARM. The research effort is focused on designing a lightweight and ergonomic upper-limb rehabilitation exoskeleton capable of producing diverse and perceptually rich training scenarios. To this end, the knowledge available in the literature of rehabilitation robotics is used along with formal conceptual design techniques. This paper briefly reviews the systematic approach used for design of the exoskeleton, and elaborates on the specific details of the proposed design concept and its advantages over other design possibilities. The kinematic structure of CLEVER ARM has eight degrees of freedom supporting the motion of shoulder girdle, glenohumeral joint, elbow and wrist. Six degrees of freedom of the exoskeleton are active, and the two degrees of freedom supporting the wrist motion are passive. Kinematics of the proposed design is studied analytically and experimentally with the aid of a 3D printed prototype. The paper is concluded by some remarks on the optimization of the design, motorization of device, and the fabrication challenges.**

I. INTRODUCTION

Stroke affects an increasing portion of the aging population of the world, leaving many of the survivors with different levels and forms of disability. Post stroke rehabilitation helps patients relearn some of the motor skills lost during stroke. This is believed to be achieved by neuroplasticity of the brain, i.e. the brain's ability to reorganize itself through forming new neural connections [1]. Rehabilitation therapy is the standard treatment for patients who have undergone stroke, and has proven to be effective in improving the range of motion (ROM) and performance based impairment indices (such as Fugl-Meyer [2, 3]). Current therapies heavily rely on physical and occupational therapists. Economic reasons, limitations on the number of available professional staff, and the labor intensive nature of the rehabilitation therapy hinder high intensity and long therapy sessions for stroke patients [4]. This situation is expected to deteriorate in the future as the population of the world grows older. The growing need for rehabilitation, along with dependency of rehabilitation effectiveness on the intensity of trainings [3], signifies the importance of a system that can be used alongside skilled therapists.

The inherent capabilities of robotics systems in producing high intensity, repeatable, and precisely controllable motions make them desirable for rehabilitation purposes [5]. End effector based systems [6-8] and exoskeletons [9-12] are two category of the robotic systems designed to provide automated therapy to stroke patients. While end effector based systems precede exoskeletons, results of studies have proven that the latter category out performs the former by providing more control over the motion of the paretic limb [13]. Despite the advantages, there are major issues associated with kinematic compatibility of exoskeletons with human arm, making design of prosthetic devices challenging.

It is well established that kinematics of biological joints is complex, and difficult to model and replicate with mechanical systems [14]. Misalignment between the axis or center of biological and robotic joints can result in large interaction forces (hyperstaticity) at the human-robot interfaces, making the device uncomfortable and in extreme case dangerous to the patient [15]. Incorporating additional degrees of freedom (DOF) within the structure of exoskeleton has been the underlying principle used for resolving this issue. Depending on the location of these additional degrees of freedom, and whether they are actuated or passive, various solutions has been used by different exoskeletons to address the joint misalignment issue. The additional degrees of freedom used within the structure of the exoskeletons can be active and directly actuated by the control system (e.g. MGA exoskeleton [16]), mechanically coupled to other degrees of freedom (e.g. ARMin exoskeleton [9, 17]), totally passive (e.g. Dampace [18]) or a combination of the aforementioned cases (e.g. IntelliArm [12]). From another perspective, additional degrees of freedom could be categorized as joints used to model the complex behavior of the anatomical joints (e.g. IntelliArm exoskeleton which uses 6 DOF to model the shoulder complex [12]), or as passive DOFs integrated into the physical human robot interface to avoid transmission of reaction forces and moments in certain directions between the device and human arm (e.g. ABLE exoskeleton [11]).

Despite all the challenges, several exoskeletons have been successfully built and tested on stroke patients. The results of the studies show that using exoskeletons for rehabilitation is as effective as conventional therapy, even superior in some cases [2, 3]. While these results are rather promising, it is desired to further increase effectiveness of exoskeletons. CLEVER ARM (Compact, Low-weight, Ergonomic, Virtual/Augmented Reality Enhanced Rehabilitation ARM) is a novel upper-limb exoskeleton for rehabilitation of stroke patients, designed to target the functional recovery of stroke patients by providing trainings for activities of daily living (ADL). Achieving an ergonomic design by incorporating sufficient degrees of freedom, and improving the portability of the device through a compact and low weight design, have been the objectives of the design procedure. The device is equipped with emerging technologies such as augmented and virtual reality to enable diverse, task specific, and immersive

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training scenarios. This paper briefly reviews the systematic approach used for design of the exoskeleton, and elaborates on specific details of the proposed design with a focus on its kinematic structure.

CLEVER ARM has six active, and two passive degrees of freedom, allowing the motion of shoulder girdle, glenohumeral (GH) joint, elbow, and wrist. An active degree of freedom is used for assisting Flexion/Extension of the elbow, while the remaining five active degrees of freedom are used in design of the device shoulder to improve the ergonomics of the device. Having five degrees of freedom, the proposed shoulder design supports the 2D motion of GH joint center on the body frontal plane. The two passive degrees allow the pronation/supination, and flexion/extension motions of the wrist. The adjustable device links can accommodate a large spectrum of people with different body dimensions (10 to 90 percentile of upper-limbs sizes reported in the literature [19]). This paper provides analytical and experimental kinematic analysis on the proposed design. It is shown that CLEVER ARM has a large workspace, covering a major portion of healthy subjects' workspace. More importantly, the kinematic singularities of the system are near the boundaries of the reachable workspace of a healthy human, and far from the ADL workspace. The final section of the paper discusses the motorization of the design, manufacturing of the device body, and the future works.

II. Conceptual Design

Design of an exoskeleton includes various aspects such as the design of kinematic structure, actuation mechanisms, and control architecture. Kinematic structure of an exoskeleton is the most fundamental block of its design, and is determinant of functional capabilities of the device. Exploring the space of possible design ideas, thoroughly and in a systematic way, with no bias towards current available designs is challenging. To overcome these issues, a systematic design approach based on the conceptual design techniques was used. Analyzing the functionality of system in an abstract level not only fosters inventiveness, but also provides a means for evaluation and categorization of available design concepts. Using the convention of Pahl and Beitz [20], the functional model in Fig. 1 is proposed for the rehabilitation exoskeleton. The "Attach/Detach" blocks model the physical interfaces between the body and the device and the "Control" block is responsible for actuating and controlling the behavior of device such as the therapy type, assistance level and emergency stops. "Interact with Arm" is a functional block modeling the physical interaction of the exoskeleton with human arm. This block captures the essence of main functionality expected from a rehabilitation exoskeleton. Fig. 2 shows the "Functional Decomposition" of this block clarifying the sub functionalities needed.

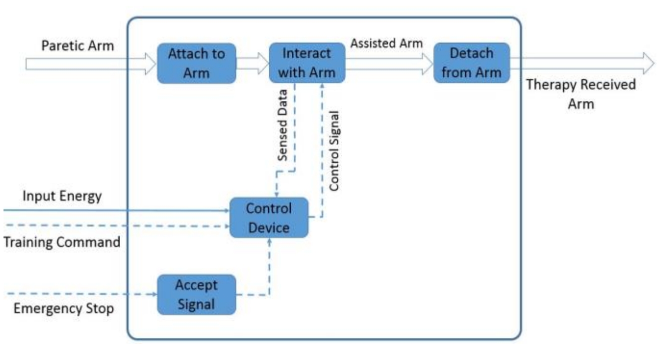

Figure 1. Functional model proposed for an exoskeleton

The interaction of exoskeleton with the patient arm can be studied in two levels: the therapeutic and kinematic interactions. Rehabilitation exoskeletons can provide therapy in assistive (partial or full) or resistive modes based on the higher level training command. Therefore, sub-functions of the "Provide Therapy" functionality are directly related to how the device is actuated and how the forces required to achieve the therapeutic goals are devised. On the other hand, kinematic compatibility of the device is directly related to how the device can conform to human arm, and thus can be analyzed in terms of the number of degrees of freedom in the device to support a certain motion. In other words, "Conform to Arm" block focuses on how the device should be designed not to hinder the natural motion of the arm.

The two sub functions of the "Interact with Arm" block are closely interconnected. Distinguishing these two units for active exoskeletons is so challenging that classifying them as two sub functionalities might seem unnecessary. This is because providing corrective intervention in active exoskeleton is via the motion of the device that forces the paretic arm to conform to the exoskeleton. However, in broader scope they represent two separate functionalities. To clarify this, consider passive exoskeletons that only provide partial weight support to patients.

Functional modeling is the first step in determining how to achieve a certain functionality in an abstract level, and it is an essential step for generation of new ideas. Using the functional modeling and functional decomposition of the system, various idea generation approaches were examined. Determining the number of degrees of freedom allocated for each block in the functional decomposition of the "Conform to Arm" and identifying mechanisms that could achieve the desired motion were the key steps in the generation of ideas. Combining the ideas for each functionality, several design concepts were achieved. The details of the idea generation, concept generation based on the diffeomorphism matrices, and concept evaluation processes are not included in this paper due to space limitations. Only the selected design concept and its advantages to other design possibilities is detailed in Section III. The selected design concept was optimized to achieve larger range of motion through an iterative process. Fig. 3 shows the 3D printed miniature maquettes of the device illustrating the evolution of the selected concept during the optimization phase of the design.

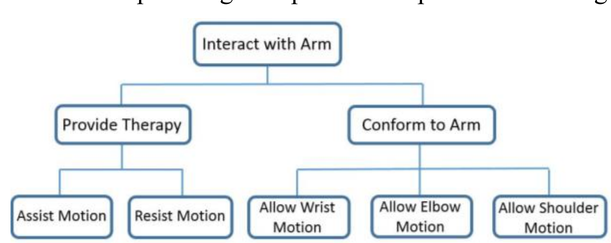

Figure 2. Functional decomposition of "Interact with Arm" block

III. Mechanical Specifications of CLEVER ARM

CLEVER ARM has eight degrees of freedom supporting the motion of shoulder girdle, GH joint, elbow, and wrist. Fig. 4 shows the CAD model of the exoskeleton on a dummy human model, and the rendered schematics of the device.

Three hinged joints, constituting a spherical linkage, is used to provide the three DOF required for the motion of GH joint. Several factors such as the shape, geometric properties of the links, and the angle between the consecutive axes of rotation can be considered in design of the shoulder joint. Circular link shapes is chosen for compactness considerations and stress bearing properties of uniformly curved structures. It is important to note that the axes of the circular links of the shoulder joint do not correspond to the biological joints of the human. The angular length of the circular links, and the angles connecting the device shoulder to the inner shoulder DOFs and the upper arm link, were chosen during the design optimization phase. The objective of the optimization process was to ensure removing singularities from the reachable workspace of the healthy human, maximizing the device workspace while avoiding possible physical interference between the device and the body parts such as the patient head, and to achieve a compact design.

The motion of the GH joint and the inner shoulder are supported by five degrees of freedom in the design of CLEVER ARM. As the arm is elevated, the group of bones constituting the shoulder girdle undergo a complicated motion which results in the displacement of the GH joint center in the 3D space. While this motion is noticeable in the superior/inferior directions, the displacement is negligible in the dorsal/ventral directions. CLEVER ARM uses two active

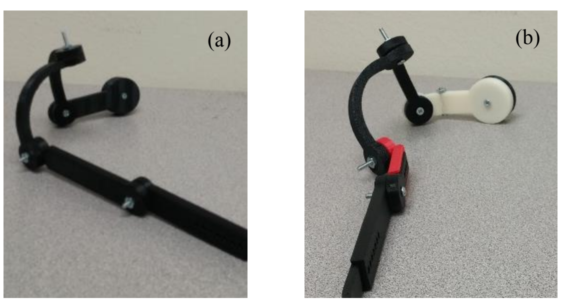

Figure 3. Evolution of the Winner Concept (a) before, and (b) after optimization

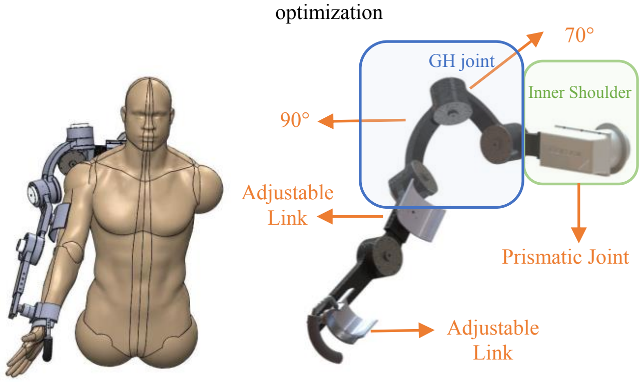

Figure 4. CLEVER ARM mechanical design

degrees of freedom (a revolute joint followed by a prismatic joint) to model the displacement of GH joint center in the frontal plane of human body. Using two degrees of freedom allows accurate tracking of GH joint center path on the frontal plane without approximating it as a circular path.

The degrees of freedom used to allow the displacement of GH joint center for the exoskeleton are active and “softly” coupled to the arm elevation through the control architecture. Soft coupling, as opposed to the mechanical coupling, refers to the continuous adjustability of the properties of the coupling through the control software. The authors believe that using soft coupling approach to address the shoulder misalignment issue is advantageous to using mechanical coupling through design of mechanisms or using passive degrees of freedom for self-alignment of the device with the body. Using a mechanical coupling between the arm elevation and the motion of inner shoulder requires the design of a complicated mechanism, continuous adjustment of which for individual patients is not practically possible. Considering the natural variations in the motion of GH joint center among different people, designing a fixed structure based on the experimental data collected from healthy subjects cannot be an optimal solution to the joint misalignment issue. On the other hand, integrating passive degrees of freedom in the exoskeleton results in sensitivity of the structure to external forces such as gravity, and interaction forces with physical world. For example, self-aligning systems cannot be used for training scenarios where force exchange can occur between the paretic arm and healthy arm or the physical world. This limits the possible trainings to virtual scenarios where no physical interactions between the device and the external world exist. Moreover, these systems require precise design considerations to isolate the effect of gravity on unactuated DOFs.

As Fig. 4 shows, the inner shoulder design of CLEVER ARM can move all the three axes of the shoulder structure in 3D space in accordance with the control structure, placing the center of the exoskeleton shoulder on a circular strip encompassed by two concentric circles, the radii of which are determined by the range of motion of the prismatic joint. The upper arm link attaching to the patient arm, is connected to the shoulder joint with a 35 degree angle. This link includes the main physical interaction point between the exoskeleton and the patient arm. The 35° angle in the geometry of the link, decreases the gap between the upper arm and the corresponding link in the exoskeleton, resulting a more stable interface between the device and the arm, and a reduced volume occupied by the device.

Flexion and extension of the elbow is supported by an active revolute joint connecting the device upper-arm to the forearm link. Adjustability of the device’s upper arm and forearm links can assure a close alignment of the exoskeleton joint to the patient elbow joint. Pronation and supination of the forearm is realized by a passive degree of freedom, presented as a semi-circular slider-guide mechanism around the patient wrist. The circular structure housing the rail of the wrist slider is loosely strapped around the patient wrist to secure the fore-arm to the device, and prevent the slip off of the patients grip. The gripper of the exoskeleton is the other physical interaction point between the device and the patient body. As seen in Fig.4, the hinged connection between the gripper and the semi-circular slider, enables the passive flexion/extension of the wrist. As mentioned earlier, the length of the upper arm, frontal arm, and the inner shoulder links of the proposed structure can be adjusted based on physical dimensions of the patient body.

IV. CLEVER ARM KINEMATICS

To study the kinematics of the device, Denavit-Hartenberg convention was used. Fig. 5-a shows the assignment of the coordinate systems in the fully extended configuration of the exoskeleton. The Denavit-Hartenberg parameters were computed using the standard procedure (see Table I) where p_1 through p_6 are the physical parameters specified on Fig. 5-a. While p_1 and p_2 are constants, other parameters can be changed by adjusting the length of the corresponding links based on the patient body dimensions.

The shoulder of exoskeleton can undergo two gimbal lock configurations. The first of the two configurations is depicted in Fig. 5 where $\theta_4 = 0°$ and the fore-arm makes an angle of 135° relative to y_0 axis. Since the range of motion for horizontal adduction of the arm is 135° relative to y_0 axis [21] this singular configuration is out of the reachable workspace. The other singular configuration occurs when $\theta_4 = 180°$. This singular configuration happens at -5° relative to the y_0 axis and corresponds to the horizontal adduction of the arm in the posterior direction of the frontal plane. Although this configuration is in the achievable work space, it is definitely outside the ADL workspace.

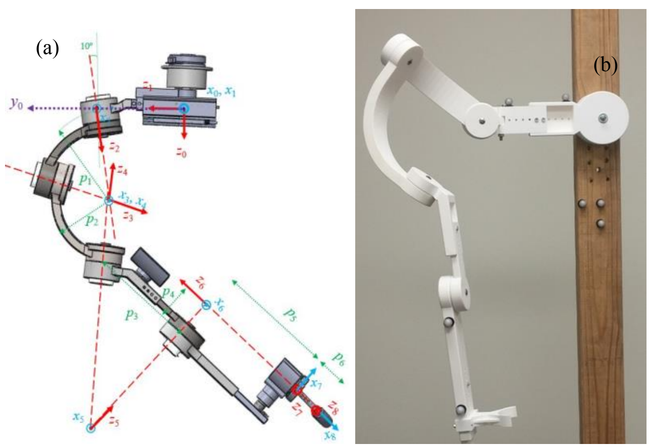

Figure 5. (a) DH coordinate frame, (b) passive prototype with reflectors

TABLE I. EXOSKELETON DH PARAMETERS

Link	DH Parameters			
	a_i	α_i	d_i	θ_i
1	0	-90°	0	θ_1^*
2	0	100°	d_2^*	0
3	0	70°	p_1	θ_3^*
4	0	90°	0	θ_4^*
5	0	-35°	$-(p_2 + p_3/cos(55^0))$	θ_5^*
6	0	90°	$p_3 tan\,(55^0) + p_4$	θ_6^*
7	0	90°	$-\,p_5$	θ_7^*
8	p_6	0	0	θ_8^*

Compatibility of the designed exoskeleton with the natural motion of the human arm was verified by studying the supported range of motion experimentally. To this end, the replica of the kinematic structure of device, (with slight modifications in the gripper due to manufacturing considerations) was 3D printed in full scale. Since the axes of rotation of the exoskeleton shoulder are not biologic axes of rotations of the arm, studying their range of motion cannot be conclusive for determining the supported range of motion of the device. Therefore, with the aid of the 3D printed prototype, the range of motion of the exoskeleton, was found using the motion capture system (Vicon MX system, Oxford, UK). Two reflectors were placed on each segment of the exoskeleton and three reflectors were placed on the base of the device to define the body coordinate system. Fig. 5-b shows the 3D printed prototype and the reflector placement. By tracking the position of the two markers, the orientation of the device arm was determined with respect to the body frame, and the achievable range of motion was calculated by manual actuation of the exoskeleton joints. Fig. 6 shows an example of the captured data with a human body model. The dashed and dotted curves show the path of the two reflectors on the forearm.

Table II compares the range of motion of CLEVER ARM, ROM of a healthy arm, and ROM required for performing ADL as reported in the literature. It is important to note that the full range of motion supported by device is larger than the values reported in Table II for some degrees of freedom. The ROM values in the table denoted by an asterisk, are the values that are limited by the ROM of healthy arm. Abbreviations in the first row of the table stand for shoulder flexion extension, abduction adduction, horizontal abduction adduction, elbow flexion extension, forearm pronation supination and wrist flexion extension respectively. The range of motion for the internal/external rotation of shoulder is not included since it depends on the elevation and horizontal abduction of the arm. As Table II shows, the ROM of the exoskeleton is close to the ROM of healthy human arm, fully covering the ROM needed for ADL tasks. The two gimbal lock configurations mentioned above, limit the achievable horizontal abduction and adduction of the arm and thus determine the range of motion for horizontal abduction-adduction. However, the limits on the achievable pronation-supination is due to practical limitations on manufacturing of semicircular bearings.

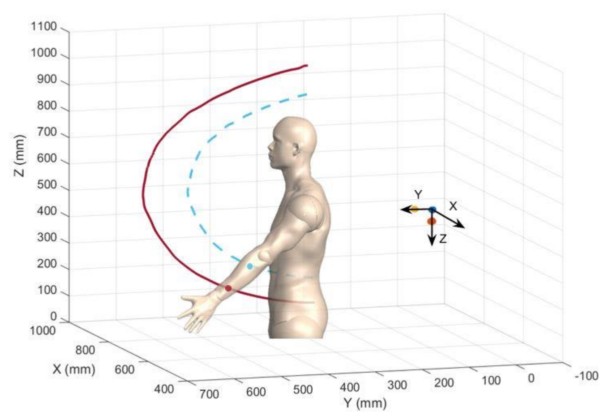

Figure 6. Captured motion Shoulder Flexion/Extension

TABLE II. RANGE OF MOTION

	Sh. Fl.	*Sh. Ab.*	*Sh. HA.*	*Elb. Fl.*	*Arm Pr.*	*Wr. Fl.*
CL. ARM	180*	180*	140	150*	155	160*
ADL[10]	110	100	130	150	150	115
Healthy Arm [21]	180	180	180	150	180	160

* limited by the range of motion of the human subject

V. MOTORIZATION AND FABRICATION PROCESS

Weight optimization and compactness of the device were two important criteria in choosing components for motorization of the design. While cable-based systems have been effective solution for decreasing the inertia experienced by the patient, they cannot improve the portability and overall weight of the device. Pneumatic/hydraulic actuators have a similar situation due to the weight of their compressor units. Electric motors coupled with zero backlash strain wave gearing systems (Harmonic Drive LLC), were chosen due to their exceptional torque to weight ratio, compactness and zero backlash. The prismatic joint in the design of the exoskeleton was realized by a direct drive linear actuator, to avoid the backlash caused by mechanisms used for transforming rotary motion to linear motion.

The choice of actuation units were based on the torque values required for ADL tasks and the torque required for cancelling the weight and the inertial effects of the exoskeleton. The ADL torque values reported in the literature were adjusted to consider the variations in the weight of patients to ensure that the actuators of the device are capable of supporting the rehabilitation needs of a large spectrum of patients. Table III shows the available force and torque at each actuated degree of freedom of the device.

TABLE III. TECHNICAL DETAILS OF ACTUATION UNITS

Joint	**1**	**2**	**3, 4, 5**	**6**
Available Torque/Force	53.3	58	31.9	21.44
Actuator	Maxon EC-90 flat	Tecnotion UM 06 Linear Act.	Maxon EC-60 flat	Maxon EC-45 flat
Gear Unit	SHD 20-160	N/A	SHD 17-100	SHD 20-160
Unit	N.m	N	N.m	N.m

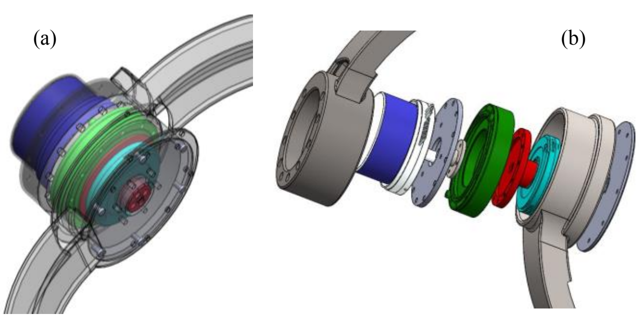

Figure 7. Inter-joint structure: (a) collapsed view, (b) exploded view, motor (blue), HD (green), flange/torsional spting (red), encoder (cyan)

To improve the back-drivability of the device, two measures were considered in the hardware design. Firstly, the pHRIs can be equipped with 6 DoF force/torque sensors. Moreover, the inter-joint structure are designed to be able to accommodate the torsional spring required for Series Elastic Actuators. Figure 7 shows the joint design of the exoskeleton.

Choice of material and fabrication method for various parts of the exoskeleton has a profound impact on the weight of the whole device. Strength to weight ratio, the practical challenges such as precision of fabrication process and the overall cost of the device body are some of the important factors to be considered. Carbon fiber has been considered an ideal candidate for body of exoskeletons. While carbon fiber possess many advantageous properties, design of fasteners for metal/composite interfaces, optimization of the design via computational methods are quite challenging due to the anisotropic properties of the composite materials. Recent advances in the fabrication techniques such as 3D printing of carbon fiber reinforced structures enable achieving complex geometries. Benefiting from these methods, the body of CLEVER ARM is fabricated by a combination of carbon fiber reinforced plastic, aluminum and steel alloys. Threaded inserts and screws are used for creating stable connections between metallic and composite parts.

The weight of the device body, excluding motors and the base on which the device will be mounted, in the current design is approximately 3.9 kg. Currently the initial prototype of the device is in assembly phase and will be functional in near future. Several games are also being developed in virtual and augmented reality environments to be used along with the exoskeleton in therapy sessions. These games are designed to replicate the reaching tasks used in ADL. Integration of the overall system and implementation of the developed control strategies are the immediate steps for this research.

VI. CONCLUSION

This paper details the design process and features of the CLEVER ARM, a compact and low weight upper-limb exoskeleton for rehabilitation of stroke patients. The kinematic structure of exoskeleton is designed based on formal conceptual design techniques and has eight degrees of freedom supporting the motion of shoulder girdle, glenohumeral joint, elbow and wrist. This manuscript briefly reviews the systematic design framework and elaborates more on the specific details of the proposed design concept and its advantages over other design possibilities. Additionally, kinematic analysis of the device is done computationally and experimentally using a 3D printed prototype and Vicon motion capture system. It is shown that the workspace and range of motion of CLEVER ARM is larger than what is required for ADL and is comparable to that of healthy human arm. It is also shown that kinematic singularities of shoulder are outside the ADL workspace for healthy human. Finally, several aspects of the device motorization and fabrication process are discussed.

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