Purposeful Proposal for CP-afflicted Upper Limbs Exoskeletons

Jinan Charafeddine, Ibrahim Maassarani, Sylvain Chevallier, Samer Alfayad

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Jinan CHARAFEDDINE[1,2,3], Ibrahim MAASSARANI[2], Sylvain CHEVALLIER[1], and Samer ALFAYAD[3]

1- LISV, Laboratory Systems Engineering of Versailles
Paris Saclay university, Vélizy, France

2-ULFG, Doctoral School for Sciences and Technology
Lebanese university, Tripoli, Lebanon

3- IBISC, Laboratoire d'Informatique, BioInformatique, Systèmes Complexes
Paris-Saclay university, Évry, France

***Abstract*— Cerebral Palsy (CP) is a debilitating neurological disorder that reduces motor function for children with CP. This paper presents the latest trends in the development of the arm exoskeleton for children afflicted by CP. Furthermore, it discusses the prospects for achieving an optimal outcome in rehabilitation and assistance. Nine upper limb exoskeletons, which targeted CP-afflicted children and were developed in recent years, are presented. Three of these exoskeletons are most commonly used in rehabilitation, and the other six are used for assistive purposes. Henceforth, it discusses when CP-afflicted children can make good use of this rehabilitation or assistance. In conclusion, this research should focus on a scalable upper limb exoskeleton that would benefit the majority of children afflicted by CP.**

$keywords:\ CP-afflicted,\ Exoskeleton,\ Upper\ limbs$

I. Introduction

Upper body movements in children are afflicted by central nervous system injuries, where the most prominent is cerebral palsy (CP) [1]. The CP results in weakness or spasticity in the upper or lower muscles of the body, or even both. When the upper body is injured, children cannot move their limbs freely. Moreover, upper limb weakness or spasticity limits a CP-afflicted child's autonomy in most daily activities, such as eating, getting dressed, and playing [2]. In the past few years, numerous efficient rehabilitation exoskeletons targeting the upper limb have been developed to improve the quality of life and support motor function for patients Fig.1, e.g., ARMIN III, CAREX, IntelliArm, USEFUL-7, ETS-MARSE, RUPERT, and CADEN-7... [3]. However, these devices are mainly aimed at Stroke-afflicted adults. As they do not fit children's size, the latter devices offer limited options to CP-afflicted children. Children's growth and muscle force must be taken into account [4]. In this context, our study aims to highlight essential prospects that meet the previously mentioned requirements. The rest of this paper is organized as follows: Section II- presents the problem and the benefits of the proposed solution, and details the anatomy of upper limbs used for designing arm exoskeletons. Section III- consists of the state-of-the-art of

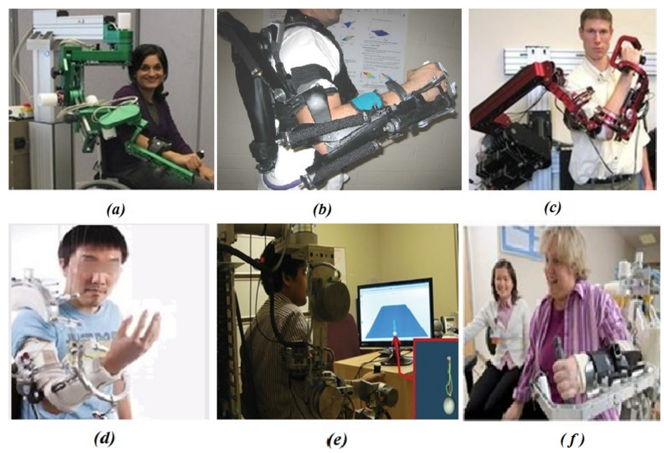

Fig. 1. Upper limb exoskeletons for Stroke-afflicted adults: (a) ARMIN III; (b) RUPERT; (c) CADEN-7; (d) CAREX; (e) ETS-MARSE; (f) IntelliArm.

upper limbs exoskeletons for the CP-afflicted. Section IV- discusses the challenges. Finally, Section V- concludes this paper.

II. Upper Limb Biomechanics and Diagnoses in cerebral palsy

An exoskeleton is a complex device that is generally designed according to the anatomy of the human skeleton to ensure that the user's joint axis and the gadget are well aligned. Exoskeleton joints misaligned from a patient's body produce erroneous forces or torques, which cause discomfort, pain, and injuries. Exoskeletons that imitate the kinematics and dynamics of the upper limb to support the user efficiently are challenging to develop due to the complex anatomy of the upper limb [5].

A. Upper Limb Biomechanics

There is no kinematic model for the human upper limb in the biomechanics literature that could help design exoskeletons. However, the exoskeleton must replicate the kinematics and dynamics of the human musculoskeletal structure to

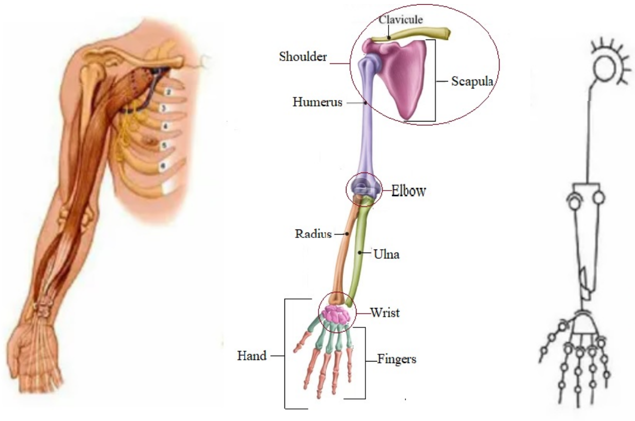

Fig. 2. Illustration of the upper limb Anatomy.

support limb motion. Therefore, most of these devices are designed to simulate the anatomy of the human skeleton. The latter guarantees proper alignment between the joint axis and the device, following the detailed anatomy in Fig.2. For designing an upper limb exoskeleton, many designers relied on dividing the upper limb into four parts [6]. - The shoulder complex: performs the majority of body joints' movements. It is composed of four joints and three bones. Its simplest model consists of three DOF, which account for the three main movements (flexion-extension (FE), abduction–adduction (AA), and internal-external rotation (IE)).

- The elbow complex: composed of two joints and three bones. It allows two movements, FE and pronation–supination (PS).

- The wrist: allows two movements, FE and radial–ulnar deviation (RU). The rotation axes of FE and RU are coincident.

- The hand and fingers: FE of all fingers and AA of the thumb.

B. Cerebral Palsy (CP)

CP results from damage to the brain of the fetus or infant. These non-progressive lesions afflict a set of permanent movement and posture disorders, which leads to activity limitations. CP is the most common cause of physical disability for children, where approximately 3 /1000 children in the world suffer from it [1]. CP may affect the upper limbs and lead to progressive deterioration of motor function. The biggest problem is that CP is a lifelong condition that hits patients of young age [7].

Regarding upper limb function, CP is classified by Manual Ability Classification System (MACS). The speed and quality of handling determine the MACS score or level. This level indicates how much the patient benefits from gravity compensation at the upper limb joints to improve his motor function. The level of benefit is higher when the MACS score is lower, and reaches lower levels when the MACS score increases and approaches a value of five [8].

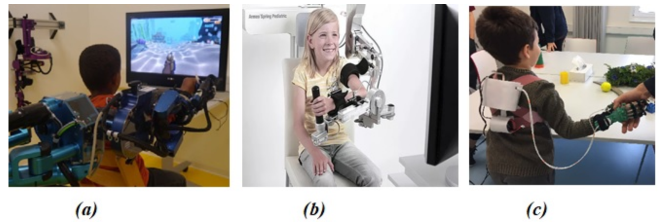

Fig. 3. CP-afflicted Rehabilitation Exoskeletons: (a) ChARMin; (b) Armeo Spring ; (c) IOTA .

III. Upper Limb exoskeletons

Existing upper limb exoskeletons for CP-afflicted children with impaired arm motor function can be classified using several methods, such as the number of active DOF and supported movements, the mode of actuation, and application domain (assistance or rehabilitation). A total of nine upper limb exoskeletons were developed in recent years and aimed at CP-afflicted children. Three of them are most commonly used in rehabilitation, and six are for assistive purposes.

A. CP-afflicted Rehabilitation Exoskeletons

Rehabilitation with exoskeletons has advantages over traditional therapy. Its main goal is to assist therapists and reduce their workload. The rehabilitation exoskeletons do not become fatigued as the therapist does, and an exoskeleton can accurately control the assistance to match the patient's need. This type of exoskeleton is used in CP-afflicted rehabilitation for long training sessions. Three upper limb exoskeletons are currently used in therapy for CP-afflicted patients, as presented in Fig. 3. These exoskeletons are:

1) ChARMin: Presented by Keller, U. et al, 2016 [8], created with a modular approach to adjust to different arm sizes, with 6 DOF, to support (Elbow-FE, Forearm-PS, wRIST-fe), 3 DOF at the shoulder, 1 at the elbow, 1 at the forearm, and 1 at the wrist. The design distinguishes between three groups: i) children of 5 years and older, for whom the proximal module is is the same. ii) children aged between 5 and 13, with a small distal module. iii) children that are 13 and older, where the distal module is large. This exoskeleton is active and provides support for the arm joint during movement, improving the child's quality in activities of daily living (ADL).

2) Armeo Spring: Presented by Cimolin, V . et al, 2019 [9], built to improve motor function, with 6 DOF, to support (shoulder-FE, AA, IE; Elbow-FE, forearm-PS; Wrist- FE), 3 DOF at the shoulder, 1 at the elbow, 1 at the forearm, and 1 at the wrist. This exoskeleton attaches to the upper and lower arm of the user and is used for clinical therapy. This exoskeleton is passive and works to increase muscle strength and range of motion in different joints.

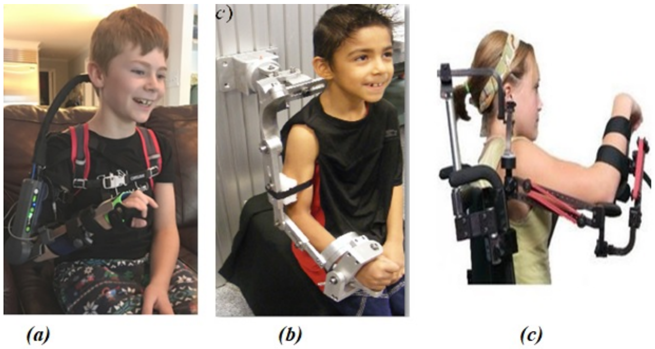

Fig. 4. CP-afflicted Assistance Exoskeletons: (a) MyoPal; (b) PEXO ; (c) WREX .

3) IOTA The Isolated Orthosis for Thumb Actuation: Presented by Aubin, P.; 2014, [10], built to help children with a thumb in palm deformity, with 2 DOF, to support hub-EF-AA. This Exoskeleton is active and allows the hand joints to move through the ranges of motion required for ADL. It is designed for home rehabilitation that complements clinic therapy.

B. CP-afflicted Assistance Exoskeletons

Similar to rehabilitation exoskeletons, assistance exoskeletons provide good training. These devices can be available for home use cases at a lower acquisition cost. The possibility of using the exoskeleton at home in ADL is of utmost importance as it further develops the skills gained during clinic therapy. Many upper limb exoskeletons are currently used for assisting CP-afflicted patients, where 3 models are presented in Fig.4. We list 6 of these exoskeletons:

1) MyoPal: Soon to be available [11], still under development by Myomo, a new version of the MyoPro designed for children aged 5 or more. The main goal is to assist the user by detecting his movement intention. It is a powered brace that may help restore functions to CP-afflicted children, built with 2 DOF, to support elbow-FE, and Thumb- and Digits–FE. This exoskeleton is active; electromyography (EMG) detects movement intention, where this intention is represented by an input signal fed to an actuator that assists this movement.

2) Soft Exoskeleton: Presented by Kokkoni, E et al, 2020 [12]. This exoskeleton aims at assisting and training upper extremity movements for infants, with 4 DOF, to support Shoulder-AA and Elbow-FE, (1 at each shoulder (AA) and 1 at each elbow (FE)), testing for an infant having an average age of 12-months. The goal is to adapt the device to changes in real-time. This exoskeleton is active and uses EMG to adjust the controlled device in real-time.

3) PEXO: Presented by Bützer, T. et al. 2019 [13], with 3 DOF, to support Thumb OR and Digits EF, hand exoskeleton designed for children aged between 6 and 12. PEXO is an active exoskeleton controlled by EMG for children with permanent disabilities. Designed for home use as a complement of conventional treatment.

4) WREX: Introduced in by T.Haumont, T. Rahman, et al., 2011 [14], further developed by M Gunn, et al., 2015 [15], built to provide gravity compensation at the arm and forearm with 4 DOF, to support Shoulder-FE, AA, and Elbow-FE. WREX is designed for children older than 1 year. It is a passive exoskeleton that exploits the gravity compensation provided by elastic elements (e.g., rubber bands or springs) and assists a user in moving his upper limbs with fewer restraints.

5) P-WREX : Presented by T.Rahmn, et al., 2014 [16], design inspired by WREX. Built with the same specifications but to fit toddlers (3–8 months old). Passive actuator.

6) Hand Exoskeleton: Presented by Bianchi, M. et al., 2018 [17], built to assist hand opening, with 2 DOF, to support digits-FE, adaptative to the child's hand. It is a passive exoskeleton, and its mechanism follows the finger during the closing gesture.

In general, the existing rehabilitation exoskeletons outperform the assistance ones. The former allows the user to develop more efficiently since it uses several degrees of freedom and supports several joints simultaneously, whereas the latter is limited in terms of support.

IV. Discussion and Challenges

We noticed that most of the work in the literature regarding the current state of exoskeletons focuses on adults. In contrast, an absence persists regarding surveys on exoskeletons that aim to improve the situation of CP-Affilted children in ADL [18], and only a few reviews started to emerge as of 2019 [19]. In most cases, these exoskeletons' mechatronic design is suitable for adults in terms of physical and neural development but not for children. Hence, the priorly mentioned leads us to believe that the exoskeletons concerned with children are yet in their infancy stages of development.

Moreover, several problems facing the types of exoskeletons designed for children are mentioned in this review, like those related to the anatomical proposition to their construction and others related to narrow fields of application.

Regarding the anatomical proposition, the simplified conception of the exoskeleton design and the decomposition leads to misalignment between the exoskeleton and the joints, especially at the shoulder. It does not account for the shoulder's center of rotation that changes as the upper limb moves or grows [3]. Also, the forearm should be a closed-loop mechanism to ensure kinematic compatibility with the assistance device and that the limb is not afflicted when it grows [20]. As for the narrow fields of application, one problem with rehabilitation exoskeletons, such as ChARMin, Armeo Spring, and IOTA, is that they do not allow at-home therapy. This is due to the large size of these exoskeletons, which makes their home deployment unfeasible.

Furthermore, It is well known that interaction with other people or objects is essential in a child's social development. Clinical therapy does not allow children to interact with a typical environment, which eventually affects their development. Solutions must be found regarding wearable devices, which will improve the ADL even outside of the clinic.

Additionally, the objective of available assistance exoskeletons is to improve anti-gravity motions. The continuous support that these exoskeletons provide is ideal for children who have been diagnosed with four or five degrees of MACS. However, these devices are limited in the number of supported movements. As far as we know, there are no assistance exoskeletons that support more than two movements, while rehabilitation exoskeletons can support up to six movements.

As the last point, research and development in upper limb exoskeletons pose challenges regarding supported movement for CP-afflicted cases. Existing devices that target children do not meet expectations: the total number of existing exoskeletons for children is less than 18% compared to those available for adults [3]. The rapid growth of children makes it difficult to develop a scalable upper limb exoskeleton. It is noteworthy to mention an adult can minorly adjust the exoskeleton to fit it to his upper limb. However, this option is not available for children due to their rapid growth [10].

Hence, developing an exoskeleton for CP-afflicted children requires careful design in terms of scalability. In contrast to adults, the dimensions of the exoskeleton vary significantly from a 5-year-old to a 13-year -old. For instance, ChARMin exoskeleton is designed on the principle of scalability, but it is still limited to adult use as it cannot fit the wide range of measurements of a child. [8].

V. Conclusion

Upper limb exoskeleton aided therapy is a technology that has shown promising results facilitating motor learning. The majority is designed to fit the average adult and allows some adjustments to tighten or loosen the device, and thus, suitable for out-of-clinic use. The objective of this review was to present the need to provide similar support for CP-afflicted children that suffer from upper limb disabilities by using scalable assistance exoskeletons. Unfortunately, no known adjustable assistance exoskeleton arms offering scalability and liberty are available for teenagers and children. Two main challenges persist regarding assistance exoskeletons for children that are currently being tested: (i) scalability due to children's growth and different arm sizes within the same age range; (ii) the fewer degrees of freedom provided in contrast to rehabilitation exoskeletons used for children. Henceforth, a new design method, e.g., the proposal of a scalable assistance exoskeleton with more degrees of freedom, might be the key to assist CP-afflicted children in performing their daily routines, where it could provide a childhood that is much less dependent on clinical rehabilitation.

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