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A Brief Review on Robotic Exoskeletons for Upper Extremity Rehabilitation to Find the Gap between Research Porotype and Commercial Type

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Abstract

The number of disabled individuals due to stroke is increasing day by day and is projected to continue increasing at an alarming rate in United States. But the current amount of health professionals in physical therapy is inadequate to provide rehabilitation to these large groups. From early 1990s, researchers have been trying to develop an easy and feasible solution to this problem and lot of assistive devices both end effector type or exoskeleton type have been developed till to date. However, only a few of them have been commercialized and are being used in rehabilitation of post-stroke patients. Making the use of exoskeletons and other devices to regain lost motor function is rare. Providing therapy to this large group is quite impossible without commercializing of exoskeleton. This has motivated the authors to make a literature review and figure the reasons out that need to be solved to bridge the gap between research prototype to commercial version. This paper covers the necessity of incorporating robotic devices in rehabilitation, a brief description of existing devices particularly upper limb exoskeletons, their hardware limitations, and control issues. Our review shows that there are significant flaws in hardware design and developing control algorithm of exoskeletons to be available in rehabilitation program.

Keywords: Stroke, Rehabilitation, Exoskeleton, Upperlimb, Hardware, Control

Introduction

American heart association reports, approximately 785,000 persons experienced a new or recurrent cerebral vascular accident (CVA) or stroke annually in the United States among which number of deaths estimated at 58000 [1]. Stroke is a leading cause of serious long-term disability in the United States. The number of people living with stroke is projected to increase by 4 million by 2030 in the USA [2]. Hemiparesis/hemiplegia is the most common outcome of stroke (which leads to movement deficiency in the contralateral limbs to the side of the brain affected by the stroke) causes of losing arm motor function [3].

A large number of survivors following a stroke experience a disability like impaired upper limb resulted by loss of partial or full mobility. In addition, motor function of human upper limb can be lost due to sports injuries, trauma, occupational injuries, and spinal cord injuries [4-6]. Moreover, physical disabilities such as full or partial loss of function in the shoulder, elbow or wrist are a common impairment in the elderly people. This impairment yields several impacts on domestic life, social life as well as economy of the country. For instance, every year the total cost from lost future productivity is $124.5 billion in United States due to stroke [7]. Therefore, it is essential to restore motor function in order to perform activities of daily living (ADL) and return those individuals as early as possible into their domestic and social life, and to save revenue from being lost as well.

The recovery is partial in stroke survivors, with 15%-30% of patients permanently disabled and 20% requiring institutional care at 3 months after onset [8]. Although there are several approaches, extensive task specific repetitive movement is one of the safe and effective method to regain lost mobility of the upper limb. The individuals those got a stroke, require incessant medical care and intensive rehabilitation often requiring one-on-one manual interaction with the physical therapist [3]. However, present demands and budget restrictions makes the duration of rehabilitation program shorter.

Moreover, robotic devices have the potentiality of being used in providing therapy for a long period of time irrespective of skills and fatigue compared to manual therapy [9]. These emphasize the incorporation of robotic devices in rehabilitation therapy of post-stroke patients. Also, robotic devices can work in multi degrees of freedom with virtual reality interface and provide therapy ranging from passive to active rehabilitation. Thus integration of robotic therapy into current practice could increase the efficiency and effectiveness of therapists by alleviating the labor-intensive aspects of physical rehabilitation [10]. Furthermore previous literature advocates that robot-assisted rehabilitation in post-stroke individuals have advantages in terms of clinical and biomechanical measures to regain arm motor function in comparison with conventional treatment [10-16]. Indeed performing repetitive movements with the affected limb of the post-stroke patient obtain functional gain thereby an increase of motivation which helps to use arm further [17-20].

The robotic devices had been incorporated in physical therapy and rehabilitation program for stroke patients from two decades ago [21]. From then, researchers have developed devices both end effector type and exoskeleton type to use in rehabilitation of affected upper limb. But

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there are a few which is being used for rehabilitation program and are commercially available. To provide rehabilitation training to the large group of patients necessitates the essentiality of commercial success of these robotic devices.

In this treatise, a review was done to figure out the reasons and shortcomings that refrain upper limb exoskeletons from being used and gaining commercial success. Though many reviews on upper limb exoskeletons, but there still lack of sufficient information. For example, Jarrassé et al. [22] review include actuation, DOF, clinical study but not control method, portability, modes of therapy etc. whereas, Maciejasz et al. [23] lack review about modes of therapy. The authors want to make a complete and brief review including as much as information so that the new researchers who are going to work can have useful and valuable information at a glance. The ongoing review has particularly focused on the exoskeletons for upper limb although some other devices like end effector based type and some power assistance device to perform ADL were summarized in Table 1. The main focus of the review was why research porotype of exoskeleton did not turn itself to commercial version. This paper contains five sections. The information about various robotic devices that has been developed so far would be appeared in section-II while section-II is all about hardware issues. In section-IV, control issues need to be solved would be discussed. The section V and VI would be discussion and conclusion.

Past Works

The use of robotic devices in upper limb rehabilitation is seen to have started in the early 1990s [21]. From then, many research groups have developed robotic devices for rehabilitation of stroke patients who lost their arm motor function. In this paper, authors have made an extensive review on those devices to date. These rehabilitation robotic devices for upper limb can be classified depending on the limb is going to be connected with them. First, end-effector type – the upper limb is attached with only end-effector of the robotic device. Second, exoskeleton type – the upper limb has not only attachment with end effector but also more point of contact. Although both end effector type and exoskeleton type robotic devices has been summarized in Table 1, the upper limb exoskeletons were the focus during the study. However, the first column in table mention the name of the device or researcher who developed it whereas the second column goes for types. In this study, robotic devices are categorized based on five criteria. Firstly, end-effector type (Figure 1) or exoskeleton type (Figure 2). Secondly, robotic devices are categorized based on purpose of use of the device either it can be used for rehabilitation (Figure 3), power assistance (Figure 4) to perform ADL or both (Figure 5). The third one shows the type of actuation whereas fourth type indicates the training mode of the device. The unilateral mode involves only the movement of affected limb while bilateral mode requires the simultaneous movement of both affected and unaffected limb in similar fashion. The last category is based on the portability of the device. If it is attached to a fixed point which cannot be shifted or moved is termed as grounded. Otherwise device is ungrounded. The degrees of freedom are shown in third column whereas fourth column depicts the scope of movement of upper limb. The fifth column simply reveals the control approach that was used in the device. However, sixth column mention the therapy mode which needs to be explained. Primarily, the rehabilitation therapy could be categorized as active mode and passive mode. Further active mode might be classified as active resist and active assist [25-29]. In active assist, patient contributes in motion achievement partially but in active resistance mode, hindrance is provided to the following of predefined trajectory. In passive mode, no contribution from the patient's side to move along the predefined path. The last column in the table says about clinical test of the device. This is what really need to increase the use of robotic devices in rehabilitation therapy.

Figure 1: End effector type device (Inmotion Wrist [24]).

Hardware Issues

The early robotic assistive devices e.g., MIT Manus now In Motion [24], MIME [10] are end-effector type, most of which were built based on planar motion. The end effector type devices are simple in structure, easily adjustable as it is attached to only one point of patient's limb during therapy, low cost compared to exoskeletons [29]. But they are limited to mimic the motion of upper limb's different joints, making difficult to measure torque at limb's joints. On the other hand, exoskeletons, which have been developed during mid-2000s can depict the motion of human upper limb and therefore are more suitable at producing joint trajectories with necessary torques. The hardware of exoskeletons is more complex, heavy and requiring attention to match the natural redundancy to make sure proper joint alignment with the human anatomy. The early robotic exoskeletons for upper limb rehabilitation lacked sophistication in hardware structure and design. Some research groups have redesigned, remodeled and built updated version of what they had developed first. For example, ARMIN III [92] is successor of ARMIN-I [91], LIMPACT [71] successor of DAMPACE [67], MAHI Exo II [76,77] successor of MAHI Exo [84]. In later versions, they have done apparent modification to make the hardware soft, more functional and good-looking. Despite development of many exoskeletons, there are a few exoskeletons available in the market for post-stroke patient's upper limb rehabilitation hitherto though. The first commercial upper limb exoskeleton for rehabilitation i.e., Armin was introduced at 2011 [22,113]. By the way, the ground floor hardware issues that needs to be solved to make exoskeletons nobler would be discussed in this section.

Joint alignment with human anatomy

The anatomical structure of human upper limb is very complex and flexible. The instantaneous centres of rotation (ICR) at elbow and shoulder joints change with the joint motion [114]. The complexity of interaction between exoskeleton structure and human body is a major issue that requires attention. The incorrect alignment between exoskeleton and human upper limb makes patients uncomfortable when they are given therapy [115-119]. The intensity of uncomforting caused by tissue depression varies from annoying to pain depending

Table 1: Robotic devices for upper limb rehabilitation of post stroke patients.

Name/developer	Type	Active DOF	Scope of movements	Control approach	Modes of Operation	Clinical Test
Bi-Manu-Track [30]	eef,R e,UB,G	1	Forearm P/S, Wrist F/E	IC	Passive assist, active assist and resist	Yes (12)
Kung [31]	exo,R,e,U,G	1	Forearm P/S	FC	Active assist Passive assist	No
Colombo [32]	eef,R,e,U,G	1	Wrist F/E	AC	Active assist	Yes (8)
Song [33]	exo,R,e,U,G	1	Wrist F/E	PID, EMG	Active assist	Yes (5)
Hu [34]	eef,R,e,U,G	1	Wrist F/E	EMG	Active assist	Yes (15)
Pylatiuk [35]	exo,R,h,U,UG	1	Elbow F/E	EMG	Active assist	No
Kiguchi [36]	exo,R,e,U,G	1	Elbow F/E	EMG	Active assist	No
Cheng [37]	exo,R,e,U,G	1	Elbow F/E	EMG	Active assist	Yes (5)
MARIONET [38]	eef,R,e,U,G	1	Elbow F/E	PC	Active assist	No
Beigzadeh [39]	exo,R,e,U,G	1	Elbow F/E	EMG	Active assist	No
Hosseini [40]	exo,R,e,U,G	1	Elbow F/E	EMG	Active assist	No
Jarrett and McDaid [41]	exo,R,e,U,G	1	Elbow F/E	PD, SMC	Active assist	No
ASSIST [42]	Exo,PA,p,U,UG	1	Wrist F/E	EMG	Active assist	No
Papadopoulos [43]	exo,RP,e,U,UG	2	Shoulder A/A Shoulder F/E	-----------	Active assist	No
Freeman [44]	eef,R,e,U,G	2	Planar movement of forearm	IC	Active assist	No
BFIAMT [45]	eef,R,e,B,G	2	Axial movement of forearm	PC	Active assist Passive assist	Yes (20)
Kiguchi[36]	exo,PA,e,U,G	2	Shoulder A/A Shoulder F/E	EMG	Active assist	No
Rosen [46]	Exo,PA,e,U,G	2	Shoulder F/E Elbow F/E	EMG	Active assist	No
Khan [47]	exo,RP,e,U,UG	2	Shoulder F/E Elbow F/E	EMG	Active assist	No
Triwiyanto [48]	exo,R,e,UB,G	2	Shoulder F/E Elbow F/E	EMG	Active assist	No
ARM Guide [49]	eef,R,e,U,G	3	Axial, elevation and yaw of forearm	-----------	Active assist Passive assist resist	Yes (19)
Kiguchi [50]	exo,PA,e,U,UG	3	Shoulder A/A Shoulder F/E Elbow F/E	EMG	Active assist	No
NeReBot [51]	eef,R,e,U,G	3	Spatial movement of shoulder and elbow	PID	Active assist Passive assist	Yes (24)
CRAMER [52]	exo,R,p,U,G	3	Forearm P/S, Wrist F/E Wrist R/U	PCM	Active assist	No
InMotion WRIST [24]	eef,R,e,U,G	3	Forearm P/S, Wrist F/E Wrist R/U	IC	Active assist Passive assist resist	Yes (36)
Takaiwa [53]	eef,R,p,U,G	3	Forearm P/S, Wrist F/E Wrist R/U	IC	Active assist	No
WOTAS [54,55]	exo,R,e,U,UG	3	Elbow F/E Forearm P/S, Wrist F/E	IC	resist	Yes (10)
Rosales [56]	exo,R,e,U,UG	3	Shoulder A/A Shoulder F/E Shoulder R	-----------	Active assist Passive assist	No
Mahdavian [57]	exo,R e,U,G	3	Shoulder F/E, A/A, Elbow F/E	IC	Passive assist	No
Sharma and Ordonez [58]	exo,R e,U,G	3	Shoulder F/E, Elbow F/E Forearm P/S,	PID	Passive assist	No
ULEL [59]	exo,R e,U,G	3	Shoulder F/E, Elbow F/E Wrist F/E	EMG	Passive assist	No
ExoRob [60,61]	exo,R,e,U,G	4	Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	PID, CTC, SMC	Passive assist	No
ARMin-I [62]	exo,R,e,U,G	4	Shoulder A/A, F/E, R Elbow F/E	PD, CTC, IC	Active assist Passive assist	Yes (8)

ABLE [63]	exo,RP,e,U,G	4	Shoulder A/A, F/E, R Elbow F/E	FF	Active assist Passive assist	No
BONES [64]	exo,R,p,U,G	4	Shoulder A/A,F/E, R Elbow F/E	PC,FC	Active assist	No
Sutapun and Sangveraphunsiri [65]	exo,R,p,U,G	4	Shoulder A/A,F/E, R Elbow F/E	IC	Active assist	No
RUPERT [66]	exo,R,p,U,UG	4	Shoulder F/E Elbow F/E Forearm P/S, Wrist F/E	FFC	Active assist Passive assist	Yes (10)
Dampace [67]	exo,R,h,U,G	4	Shoulder A/A, F/E, R Elbow F/E	PC, CTC	Passive assist	No
Brackbill [68]	exo,RP,e,U,G	4	Shoulder A/A, F/E, R Elbow F/E	PD, CTC	Active assist Passive assist	No
ALEx [69,70]	exo,R,e,U,G	4	Shoulder A/A, F/E, R Elbow F/E	EMG	Active assist Passive assist	Yes (1)
LIMPACT [71]	exo,R h,U,G	4	Shoulder A/A, F/E, I/R Elbow F/E	CTC, IC	Passive assist	No
Zhou [72]	exo,R h,U,G	4	Shoulder A/A, F/E, I/R Elbow F/E	EMG	Passive assist	No
NEMS [73,74]	exo,R e,U,G	4	Shoulder A/A, F/E, I/R Elbow F/E	PID	Passive assist	No
Li [75]	exo,R e,U,G	4	Shoulder A/A, F/E Elbow F/E Forearm P/S	EMG	Passive assist	No
Pina-Martinez [32]	exo,R e,U,G	4	Shoulder A/A, F/E, R Elbow F/E	-----------	Passive assist	No
MAHI Exo II [76,77]	exo,R,e,U,UG	4	Elbow F/E Forearm P/S Wrist F/E Wrist R/U (NDA)	IC, AC	Active assist Passive assist	No
L-EXOS [78]	exo,R,e,U,G	5	Shoulder A/A, F/E, R Elbow F/E Forearm P/S	IC	Active assist Passive assist	Yes (6)
MULOS [79]	exo,RP,e,U,UG	5	Shoulder A/A, F/E, R Elbow F/E Forearm P/S	PID	Active assist Passive assist	No
MARSE-5 [80]	exo,R,e,U,G	5	Shoulder A/A, F/E, R Elbow F/E Forearm P/S	SMC	Active assist Passive assist	No
MGA [26]	exo,R,e,U,G	5	Shoulder A/A, F/E, R Elbow F/E Forearm P/S	IC, AC	Active assist Passive assist	No
T-WREX [81]	exo,R,p,U,G	5	Shoulder A/A, F/E, R Elbow F/E Finger Grasp	-------------	Active assist Passive assist	Yes (51)
RUPERT IV [82,83]	exo,R,p,U,UG	5	Shoulder A/A, F /E, R Elbow F/E Forearm P/S Wrist F/E	FFC	Active assist Passive assist	Yes (6)
MAHI [84]	exo,R,e,U,UG	5	Elbow F/E Forearm P/S Wrist F/E Wrist R/U (NDA)	IC, AC	Active assist Passive assist	No
John [85]	exo,R,e,U,UG	5	Shoulder A/A, F/E, R Elbow F/E Forearm P/S	-------------	Passive assist	No
Mushage [86]	exo,R,U,UG	5	Shoulder A/A, F/E, R Elbow F/E Wrist F/E	SMC	Active assist Passive assist	No
Kang and Wang [87]	exo,R,e,UB,UG	5	Shoulder A/A, R Elbow F/E Forearm P/S Wrist F/E	RRC	Passive assist	No
ARAMIS [88]	exo,R,e,B,G	6	Shoulder A/A, F/E, R Elbow F/E Forearm P/S wrist F/E	------------	Active assist Passive assist	Yes (14)

MIME [10,89]	eef,R,e,UB,G	6	Shoulder Elbow (NDA)	-------------	Active assist Passive assist resist	Yes (57)
Gentle/S [28,90]	eef,R,e,U,G	6	Shoulder Elbow Forearm (NDA)	------------	Active assist Passive assist resist	Yes (31)
ARMin-III [91-94]	exo,R,e,U,G	6	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, wrist F/E	PD, CTC, IC	Active assist Passive assist	No
Chen [95]	exo,R e,U,G	6	Shoulder A/A, F/E Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	------------	Passive assist	No
CABexo [96]	exo,R e,U,G	6	Shoulder A/A, F/E Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	------------	Passive assist	No
6-REXOS [97]	exo,R e,U,G	4	Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	------------	Passive assist	No
MAAT [98-100]	eef,R,e,UB,G	7	Shoulder Elbow Forearm (NDA)	------------	Active assist Passive assist	No
CADEN-7 [101]	exo,RP,e,B,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	PID, EMG	Active assist Passive assist	No
MARSE-7 [60,102]	exo,R,e,U,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	PID, CTC, EMG, SMC, SME	Active assist Passive assist	No
SRE [103]	exo,R,p,U,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	PID, IC	Active assist Passive assist	No
SUEFUL-7 [29]	exo,PA,e,U,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	EMG, FC	Active assist Passive assist	No
Umemura [104]	eef,R,h,U,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	---------------	Active assist	No
Garrido [105]	exo,R,e,U,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	AC	Active assist Passive assist	No
Rehab-Arm [106]	eef,R,h,U,G	7	Shoulder A/A, F/E, R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	PID	Active assist	No
CAREX-7 [107]	exo,R e,U,G	7	Shoulder A/A, F/E, I/R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	CTC, PID	Passive assist, Active assist	No
Kim and Kim [108]	exo,PA e,U,G	7	Shoulder A/A, F/E, I/R Elbow F/E Forearm P/S, Wrist F/E Wrist R/U	------------	Passive assist, Active assist	No

NTUH-ARM [109]	exo,R,e,U,G	9	Shoulder Elbow Forearm wrist (NDA)	PID, IC, EMG	Active assist Passive assist	No
IntelliArm [110]	exo,R,e,U,G	10	Shoulder Elbow Forearm Wrist (NDA)	VRC	Active assist	No
REHAROB [111]	eef,R,e,U,G	12	Shoulder Elbow (NDA)	---------	Active assist	Yes (8)
Hand motion assist robot [112]	exo,R,e,U,G	18	Wrist Finger (NDA)	PD	Active assist Passive assist	No

Abbreviations

Clinical test: The number inside bracket in the last column shows the number of patients.

Type: eef: End-effector type robot, exo: Exoskeleton type robot, e: Electric actuation, p: Pneumatic actuation, h: Hydraulic actuation, U: Unilateral, B: Bilateral, UB: Unilateral and Bilateral, R: Rehabilitation, PA: Power assistance, RP: Rehabilitation and Power assistance, G: Grounded-Exoskeleton's base is fixed to a location, UG: Ungrounded - base is movable.

Movements

A/A: Abduction/Adduction, F/E: Flexion/Extension, R: Internal/External rotation, P/S: Pronation/Supination, R/U: Radial/Ulnar deviation NDA: Not defined by basic anatomical movement.

Control

FC: Force control, FF: Force Feedback control, FFC: Force Forward control, PC: Position control, PD: Proportional Derivative control, PID: Proportional Integral Derivative control, CTC: Computed Torque control, IC: Impedance control, AC: Admittance control, EMG: Electromyography (EMG) based control, SMC: Sliding mode control, SME: Sliding mode control with exponential reaching law, PCM: Pulse code modulation scheme, VRC: Virtual reality based control, RC: Robust Control.

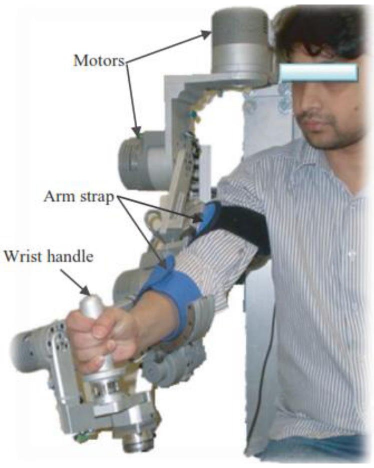

Figure 2: Exoskeleton type device (MARSE-7 [25]).

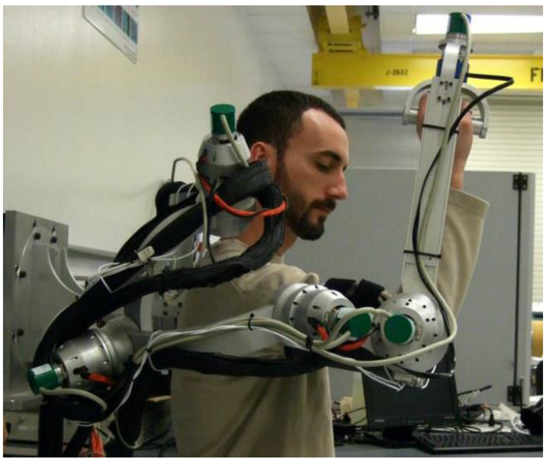

Figure 3: Rehabilitation type device (MGA exoskeleton [26]).

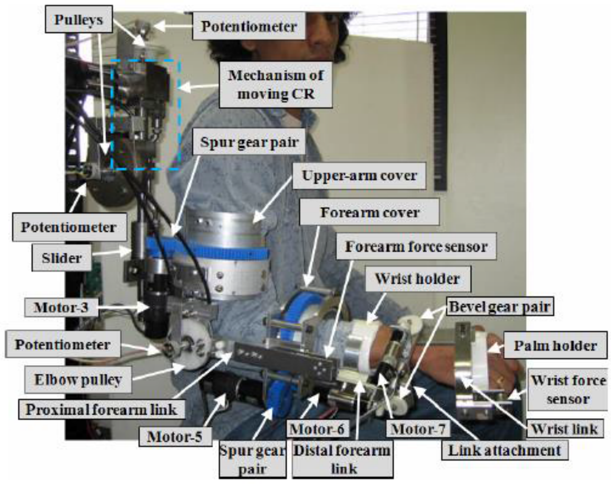

Figure 4: Power assistance device (SUEFUL-7 [27]).

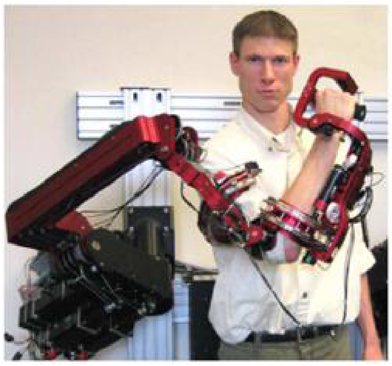

Figure 5: Both rehabilitation and power assistance type devices (CADEN-7 [28]).

on the amount of misalignment [116]. In addition, misalignments between human and robot joint axes can also occur as a result of ignoring the motion of ICR in the exoskeleton robot [118]. There have been developed a plenty of exoskeletons that used a simple ball and socket joint in producing shoulder movement [56,87,101,102,106]. Reproducing shoulder movement by a ball and socket joint is not enough to define it since there are two more movements (motions of the glenohumeral joint - elevation and rotation). These movements are involved with all other movements of the arm and varying from person to person. Though their effect is slight, it should be taken into consideration while designing rehabilitation exoskeleton. Researchers used different techniques to minimize the effect of misalignment. In MEDARM, a cable driven system is proposed to deal with the effect of shoulder ICR movement [118]. Without using any additional mechanism, some research groups solved joint alignment and shoulder translation complexities by keeping trunk moveable [78,101]. The aforementioned approaches were applied to make shoulder and elbow aligned with the mechatronic structure of exoskeleton as closely as possible. Stienen et al. [116] suggested decoupling of joint and rotations and translations which would make the exoskeletons self-aligned. The major disadvantage of this solution is complexity and the reduction in interaction stiffness. Other researchers incorporated additional mechanism to make their devices aligned with the human upper limb's joint axes, leading to produce natural redundancy and shoulder complexities in addition to ball and socket joint [26,62,81,91-93]. These projects were to find the motion of the glenohumeral joint (GH) as a function of elevation of humerus head only by rotating glenohumeral joint about the acromioclavicular joint. Carignan et al. [26] have developed an empirical equation to find vertical displacement of GH joint. Whereas, Nef et al. [92] proposed an ergonomic shoulder model that optimized the movement of humerus head for a certain body weighted patients and mentioned the range for it as well. In order to find the other weight group patients, a linear scaling factor was introduced in later one. Both the works have included an unactuated joint to move humerus head. This solution is better than previous two approaches in producing trunk movement, close to natural. But it created complexity in structure and increased the inertia. In NEMS, eight additional passive degrees of freedom with four active series elastic actuators were used for the alignment of the motor axes to the human joint axes, regardless the user's specific anthropometry sizes [73]. Such a compliant architecture makes the device safer, reliable and, comfortable. Christensen and Bai [119] proposed a novel shoulder mechanism where a double parallelogram linkage is used to overcome the effect of shoulder ICR motion [50] used a instantaneous centre of rotation mechanism with two passive DOF to produce complex shoulder movement. In recent past, Li et al. [75] proposed a number of synthesis methods of self adapting upper-limb rehabilitation exoskeletons.

Singularity

The mechanical singularity is another issue that appears in exoskeleton when two axes of exoskeleton's joints (particularly axis for shoulder internal/external rotation and axis for forearm pronation/supination) are aligned with each other, one DOF is lost and requires infinite torque to move exoskeleton away from this position. Malosio et al. [120] introduced elbow joint misalignment to get rid of singularity, limited to mimic the kinematics of upper extremity. The human upper limb has natural singularity and it does not create a trouble to move limb from singular position. Unlike human upper limb, actuators in exoskeleton requires infinite torque to move itself from singular position. Some researchers didn't consider the issue because it is rare to encounter a singular position in rehabilitation protocol [21,101]. But exoskeleton should be got rid of singularity because it can be stuck if somehow it's been in singular position. There are two areas where effort can be given to solve the issue. Researchers might address the issue in design of exoskeleton's structure or they can include it in control strategy, to make exoskeleton safe in operation and reliable.

Actuation mechanism

Actuators provide the necessary torques to run the exoskeletons. The actuator is one of those stuffs that is responsible to increase the weight of exoskeletons. Therefore, researchers are looking for actuators that have high power to weight ratio. There are three main types of actuators i.e., electrical, pneumatic and hydraulic actuators that have been used in past exoskeletons. The typical examples of exoskeletons where pneumatic actuators were used are [64,82,103]. The efficiency of pneumatic actuation depends on pressure loss due to friction, air's compressibility and purity of air. It has high power to weight ratio over electric motors. The major disadvantage is that the bandwidth which it is operating on is relatively low (5 Hz) which limit the rate at which they can respond to command signals [121]. Some research groups have used hydraulics actuation in their work [35,67] which has high power to weight ratio. But hydraulic actuator produces less efficient motion if fluid leaks, pressure loss happens. Also it requires equipment to reduce noise, what makes system more complex. To actuate the upper limb exoskeletons, electrical motors have been used in most devices [27,76,77,93,97,101,102] since electrical motors can produce large amount of torque and highly precise motion despite they are heavy compared to other two. The actuators to be used in exoskeleton should (a) be light (b) have high operating bandwidth (c) capable of producing precise motion and (d) deliver large amount of torque.

Power transmission

In order to turn research prototype of upper limb exoskeleton into commercial version, power transmission should be more novel and sophisticated which would help it make simple, low inertia and to provide required power. Incessant variable power transmission is required in exoskeleton during operation. The transmission can be done by cable drive, wire rope drive, gear train transmission, pulley drive, harmonic drive etc. Some approach used cable driven actuation to run their exoskeleton [96,103,107,]. One of the flexibility for cable drive is that it can be fitted at spots within exoskeleton where it would be hard to place other types. This kind also provides benefits in terms of low inertia and simplicity, ensures fast response times, and long range transmission of force and power but cable can easily stretch and slip which leads to produce different joint movement than the desired [107,122] proposed a cable tension programming where quadratic programming is applied to optimize the cable tensions.

In contrast, transmission that uses gear trains inherently contains some clearance between meshed teeth what causes friction and backlash [123]. Moreover, it requires lubrication, significant space for gear box and regular maintenance which discouraged researchers to use it in upper limb exoskeletons. However, some research group used harmonic drives to avoid backlash [25,92]. This transmission offers compactness, light weight, high gear ratios and high torque capability that makes it popular among research community of upper limb exoskeleton for rehabilitation [124]. Apart from overall transmission, there are some joints like the rotation about axes which are along the length of upper limb (i.e., shoulder internal/external rotation and forearm pronation/supination) are somewhat complex in regards to power transmission because placement of actuator and shaft along the axis of rotation is practically infeasible due to the anatomical configuration of the human arm. Rahman et al. [25] have developed an innovative gear mechanism where motion is transmitted from an anti-backlash gear (mounted on a motor shaft) to an open-type, custom-made meshing ring gear attached rigidly to the upper arm cup. But still there is need to come up with more novel approach in terms of lightness, compactness, functionality and fast response.

Decoupling

The interactive torques between joints hamper the exoskeleton to follow desired trajectory which is monumental for rehabilitation. For instance, if the exoskeleton is not perfectly decoupled, torque of a joint contributes to neighboring joints, leads to improper estimation of torques. Decoupling would definitely help produce smooth motion and torque as much needed [120,122]. In Auxilio, decoupled mechanism using tendon drive is used to decouple the individual joint movement [125]. But tendon can easily stretch and slip, leading to cause disrupt the power transmission which is why other research groups are not interested to this solution [122]. In addition, it makes the hardware no longer simple. However, the most of the exoskeletons (Dampace, ASSIST, AMBLE, BONES, MARSE etc.) that are currently available are not decoupled. This effect has been considered and compensated in exoskeleton's controller. This solution produces more appeal than the previous approach to the researchers since it does no change in hardware.

Backdriveability

The backdriveability is another important issue that needs to be addressed since the patients are supposed to have control sharing of movement when they are given active therapy. With the passage of time, patients regain their lost motor function, therefore exoskeleton must allow patients when they are able to move their limb on own effort. The CADEN-7, a 4 DOF exoskeleton and ABLE exoskeleton are backdriveable [63,65,101].

Control Issues

The dynamics of upper limb exoskeleton is non-linear in nature as it comprises of many links, joint, actuators and sensor. The centrifugal and Coriolis forces, and friction at joints causes non-linearity to appear in exoskeleton's manipulator dynamics. Therefore, unlike control approach used in industrial robotics, controlling of upper arm exoskeleton necessities non-linear control strategy [102]. In rehabilitation, robotic devices have been deployed to assist patients after stroke to move their impaired limb through a pre-defined trajectory. This movement uses both a linear and nonlinear approach [41,68,91] used a PD controller which has limitations of having some steady date error in trajectory tracking. On the other hand [58,60,73,74,106,107,126] used a different approach (PID) in which an integral term was added in the controller to compensates for steady state error during the robot-aided therapy. But the shortcomings of PID controller are that the joints are treated as independent and it is purely error driven which might generate a large amount of torque if exoskeleton is stuck in somewhere because of accumulation of error.

Basically, it is expected that controller used in exoskeleton should be as much as robust so that they could be compatible with the external disturbances produced by the environment where robot works. That is why research groups have been interested in using nonlinear control technique i.e., computed torque control (CTC), impedance control, admittance control, neuro-fuzzy control, sliding mode control (SMC), sliding mode control with exponential reaching law (sMERL), electromyographic (EMG) control, adaptive control etc. to pay for these issues.

Some research groups used CTC method to control the motion of their exoskeletons [67,71,107]. This approach is based on manipulator dynamics and able to handle disturbances. But it is difficult to model accurate dynamics of the manipulator since mass/inertia, damping, centrifugal and Coriolis term varies from patient to patient. In addition, generally friction is being neglected to avoid complexity in modelling. Thus, the tracking performance appreciably be reduced for CTC.

In impedance control force was being controlled in which position is given to the closed loop controller as feedback [26,109]. In those attempts, the Jacobian has been used to obtain required torques to follow the desired trajectory. But the limitation of impedance control is that system becomes unstable if the mechanical impedance is high and it requires natural dynamics as well [127]. On the contrary, admittance controller, used in many haptic devices, position was being controlled while force taken as feedback [32,84]. The main advantage of using admittance controller is that it does not require model feedforward to compensate for the natural dynamics rather it depends on the high PD gains of the joint position servo-loop to reject unmodeled dynamics [26]. However, this type of controller holds its stability until it has high impedance.

In order to control parameters (i.e., mass, length of the limb, muscle force etc.) which may vary from subject to subject, proposed sliding mode fuzzy adaption control technique for upper limb exoskeleton [124,128] used a back-propagation neural network based on EMG to follow a desired trajectory whereas [50,129] used a neuro-fuzzy adaption controller based on EMG signals. But neural network and fuzzy logic control require heavy computation. Moreover coaching staff i.e., Microsoft Kinect is used in some non-actuated exoskeleton where patients movement is going to be monitored and it provides feedback but does not participate in control directly [81].

However, one of the challenge for upper limb exoskeleton is control sharing (active therapy mode) when patients start regaining their lost motor function with the passage of time, at this stage exoskeleton must allow patients to move their limb on own attempt. This is what researchers called as much as needed control. Though in the field of upper extremity robotic devices, researchers have implemented different control scheme in order to obtain a fine control and tracking, still there are room to develop the controller more intelligent. For example, a therapist can notice whether patients are feeling any pain during rehabilitation, therefore, he/she could adjust with the situation to provide a safe therapy. In addition, the patient's muscle contraction varies with the body temperature which needs to be taken into account in control approach [130]. Also, level of disability for every patient is not equal, but same robotic device would be using for all. Moreover, most of the current exoskeletons follows desired trajectory but do not consider the force which also demands more attention. These are the issues which will make exoskeleton safe, efficient and increase its use in rehabilitation program that researchers need to consider when designing control algorithm.

Discussion

A few of the robotic devices have been tested in the clinical environment. The rests are not being able to show efficacy in rehabilitation program. The reason behind this is that exoskeletons for rehabilitation are not welcome yet in clinical setting. However, the rapid advancement in technology has accelerated the development of the upper limb exoskeleton. The researchers have been working on control method including linear, nonlinear and hybrid, control input (EMG, EEG signals, Brain signals), actuation, power transmission, sensor technologies etc. to make reliable assistive robotic devices for rehabilitation program. There are room to develop actuation, power transmission, portability, functionality, compactness and weight. Also modularity is something, offers advantages over traditional robotics in terms of reconfigurability that allows upper limb exoskeleton being used only for shoulder, elbow or wrist depending on patient's requirement, researchers working on upper limb exoskeleton wish to have in their system [131]. The exoskeleton needs high power to weight ratio with high bandwidth, simpler mechanism for transmission with minimum loss. The decoupling should be done such a way so that it would help to obtain finer coordination of joint torques but not to make the exoskeleton complex and weird posture. In addition, backdriveable exoskeleton helps to provide as much as needed torque so that patients might be taking part in motion achievement during therapy [132].

For controller design, control sharing is the most important thing which should be more novel. Doing so requires estimation of muscle force and sending it as a feedback to the controller. The factors that affect estimation of muscle force should be taken into consideration while designing control algorithm. Safety is the top priority issue, any time exoskeleton should be stopped if something goes wrong. The controller should be acting like a therapist and can adjust the operation if patients feel pain [133].

As we discussed earlier researchers have been developing many exoskeletons over last two decades, still use of exoskeleton is not common in rehabilitation and commercialized. In this paper, it is being tried to figure out the reasons why a few of devices have commercial version however there is a lot of exoskeletons are currently available. The review came up with the following design considerations for upper limb exoskeleton: low mass, excellent power/weight ratio, accurate and automatic compensation for gravity, compactness, natural redundancy, greater range of motion, safe operation, reliability in all operations, relatively low complexity and low engineering and construction cost, simple fitting and removal, comfort in wearing, low/no maintenance, portability, modularity, home use and affordable cost [80,103].

Conclusion

As mentioned earlier that the number of stroke patients is projected high and one to one rehabilitation program would be quite labor intensive and impossible due to shortage of therapist. Researchers have developed many exoskeletons for rehabilitation program which are technologically advanced. Their efficacy and reliability in therapy is still unproved because of not having much clinical evidence. This with cost constraint would limits commercialization of these exoskeletons which are already developed. Producing these exoskeletons commercially is essential. Otherwise it would not be possible to provide therapy many people. It is hoping that researchers will make new and effective solution to the reasons stated in this paper and this document would help the new researcher to direct themselves to identify reasons and thereby finding solution.

Conflict of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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