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State-of-the-Art Assistive Powered Upper Limb Exoskeletons for Elderly

Akim Kapsalyamov[1], Shahid Hussain,[1] and Prashant K. Jamwal[2,3], *Senior Member, IEEE.*

[1] Human Centred Technology Research Center, Faculty of Science and Technology, University of Canberra, Canberra, Australia

[2]Department of Electrical and Computer Engineering, Nazarbayev University, Astana, Kazakhstan.

[3]ReLive Research, Astana, Kazakhstan.

Corresponding author: P. K. Jamwal (e-mail: prashant.jamwal@nu.edu.kz).

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ABSTRACT The number of older people is growing rapidly around the world. Ageing process results in reduced or restricted mobility which is essential to perform activities of daily living. Currently, there are numerous powered assistive exoskeletons commercially available as well as are being developed to support and rehabilitate lower limbs. Significant attention is also been given to develop upper limb rehabilitation devices, however the question of what kind of assistive devices can be used by elderly group of people for their upper limbs and what technical characteristics they should incorporate is not properly researched. This paper presents the state of the art of currently available assistive exoskeletons which can be exploited to support the motions of upper limbs of elderly to perform activities of daily living. Mechanism type, degrees of freedom, type actuators and materials selected for the fabrication of these porotypes are presented in detail. Also, the type of control systems utilized for these upper limb exoskeletons are discussed in detail with the insight on the feedback signal methods. A detailed discussion on the challenges in the fields of mechanism development, actuation and control for these upper limb powered exoskeletons is presented with the opportunities for future technological developments.

INDEX TERMS: Control, elderly, exoskeleton, upper limb assistance, wearable robotic device.

I. INTRODUCTION

With the progresses made in technology and medicine in the 21st century the global share of elderly population started to increase rapidly. Based on the report from the World Health Organization (WHO) nowadays most people can expect to live up more than 60 years [1]. Based on United Nations (UN) data it is estimated that by the year of 2050 the proportion of older people will grow up to 2 billion [2]. It is projected that developing countries will be the home to more elderly people in comparison to the developed ones [3]. The estimate and projection of senior citizens increase by developed and developing regions is depicted in the Figure 1 [4].

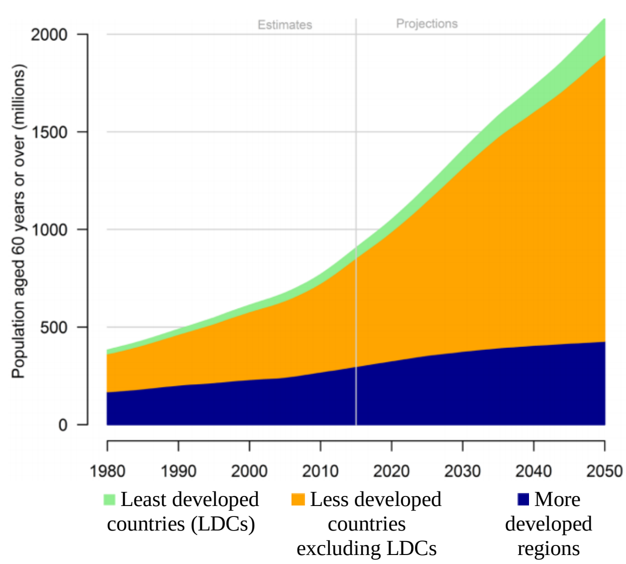


FIGURE 1. **Estimation and projection of elderly people of the age of 60 years and beyond from 1980 to 2050.**

The process of ageing causes degradation in skeletal and muscle structures, thus older people start experiencing deterioration in muscle strength and volume becoming more predisposed to various age related diseases such as sarcopenia and osteopenia [5-7]. On average, an older organism loses 3% of its muscle strength annually [8]. The results of studies reveal, that movements associated with upper limbs among elderly are also impacted due to ageing process [9-12]. The loss of muscle power in upper limbs decreases mobility and limits activities associated within daily life. There are around 15% of elderly people above age of 65 who need help to perform usual daily work [13]. To address this problem assistive technologies in terms of wearable robotic devices have been developed. Robotic upper limb exoskeletons can help to assist activities of daily living (ADL).

The purpose of this paper is to explore the currently existing wearable assistive robotic upper limb exoskeletons which can be used by elderly people to help them in performing various ADL. This paper presents the technical insights in terms of mechanism design including degrees-of-freedom (DOF) for these upper limb robotic exoskeletons, types of actuators used to power these exoskeletons and materials used for the fabrication of these exoskeletons. Also, the control strategies developed for these robotic upper limb exoskeletons are discussed in detail. A detailed discussion on the mechanism, actuation and control aspects of these upper limb robotic exoskeletons is presented. Finally, future trends and venues for further development in the field of upper limb robotic exoskeletons are discussed.

Numerous review papers have been published on the topic of upper limb exoskeletons for rehabilitation and assistive purposes [14-25]. The difference between these published review papers and this paper is that the current paper concentrates mostly on robotic upper limb devices which can be used by old people to perform their ADL, enabling them improving their life quality. This presents the contribution of this paper as compared to the published literature. As per the best knowledge of authors, no prior paper describing the technological aspects of robotic upper limb exoskeletons for elderly assistance has been reported in literature.

The upper limb exoskeleton has broad definition and to limit the scope of the current study, several inclusion and exclusion parameters were set. Firstly, the passive orthoses which do not have any motors or actuators were not considered in this work. Upper limb exoskeletons which possess only single therapeutic rehabilitation or physical augmenting (the ones which are used for military personnel to carry or lift heavy objects) purposes were not included as well. The review work has included robotic upper limb assistive devices which help to perform motions of upper limbs required for daily activities. The term *assistive* to which the current review is targeted means the device can provide additional necessary torque to help elderly in completing various physical motions. If the system incorporated both assistive together with rehabilitation purpose, it was considered as well for this review. If it is not specifically mentioned in the papers searched while writing this review that given upper limb assistive exoskeleton can be used by elderly or weak people for ADL purposes, the exoskeleton was excluded from this review. The different set of keywords such as *elderly, activities of daily living, upper limb, old people, exoskeletons, robotic, powered orthoses, assistive, device and wearable* and their combinations were used for searching the publications from databases such as Scopus, Google Scholar, IEEE Xplore, Web of Science, PubMed, ERIC, JSTOR, Directory of Open Access Journals (DOAJ) and ScienceDirect.

II. UPPER LIMB BIOMECHANICS

Upper extremity is one of the most complex part of human body. It consists of hand, wrist, forearm, elbow, arm and shoulder complex [26] as shown in Figure 2 (a). Clavicle, scapula, humerus, radious, ulna, phalanges carpals and metacarpal (Figure 2 (b)) constitute the main bones of the upper extremity. The movement of the arm depends on the synchronized interaction of three bones namely; "clavicle, scapula and humerus" and four joints named as "glenohumeral, sternoclavicular, acromuclavicular and scapulothoracic" [27].

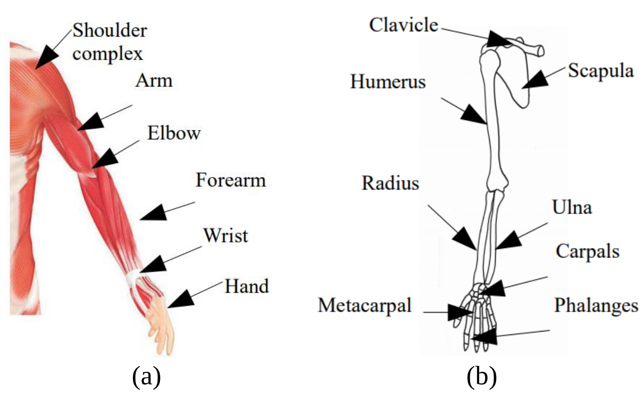


FIGURE 2. **(a) Upper limb parts with muscles; (b) main bones of upper extremity.**

Overall, the arm has seven degrees of freedom (DOF). Three DoFs are located at the shoulder complex (glenohumeral joint), whereas the elbow and the wrist joints possess two DOFs, each. Figure 3 depicts various upper extremity motions.

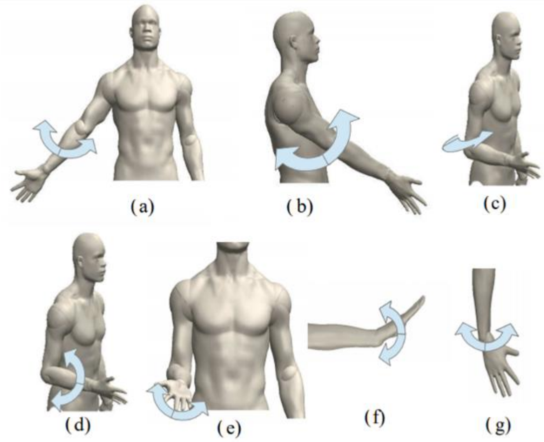


FIGURE 3. (**a) Shoulder component (Abduction and adduction). (b) Shoulder component (extension and flexion). (c) Shoulder component (rotation internally and externally). (d) Elbow component (extension and flexion). (e) Forearm component (Pronation and supination). (f) Wrist component (extension and flexion). (g) Radial-Ulnar flexion**.

Majority of ADL do not require upper limbs to be used in a full range of motion. Therefore, it is essential to determine how much range of motion for each DOF is required to perform the ADL. For instance, the normal range of flexion and extension for elbow varies from 0 to 150 degrees, and for pronation and supination is from 75 to 85 degrees [28], however the study conducted by Morrey *et al.,* indicated that performance of 15 daily activities require motions ranging from 30 to 130 degrees in elbow flexion and extension movements and 50 degrees for pronation and supination movements [29]. The usual range of motion for wrist extension goes up to 70 degrees and flexion varies between 80 to 85 degrees [30]. The range of motions of 40 people for ADL has been studied and analyzed in the work done by Ryu *et al.* [31]. The results demonstrate that in majority of daily life activities a person required to use only 70% of the total range of motion for the wrist. Knowledge of required range of motion for the performance in the daily life activities can be beneficial in the development of assistive exoskeletons for elderly people.

III. MECHANISM DESIGN

In general, powered upper limb exoskeletons are referred to the category of wearable robots which match the range of movements of human upper limbs. The mechanism structure of wearable exoskeletons works in parallel with the human limbs. Such devices are able to enhance the power of upper limbs and direct them in a specified trajectory by providing additional torques for muscles and joints [32-34].

One of the 1st concepts of upper limb assistive devices with parallel mechanism structure for disabled or weak people has been proposed in 1995 by Homma and Arai to support hand motions during ADL [35]. The concept is shown in Figure 4. The hand is attached to strings and the motions of arm are exerted by interchanging the length of each string, the motor and control parts are located on the backside of the wheelchair. The proposed design was not realized into a physical prototype.

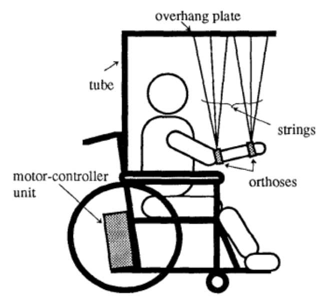
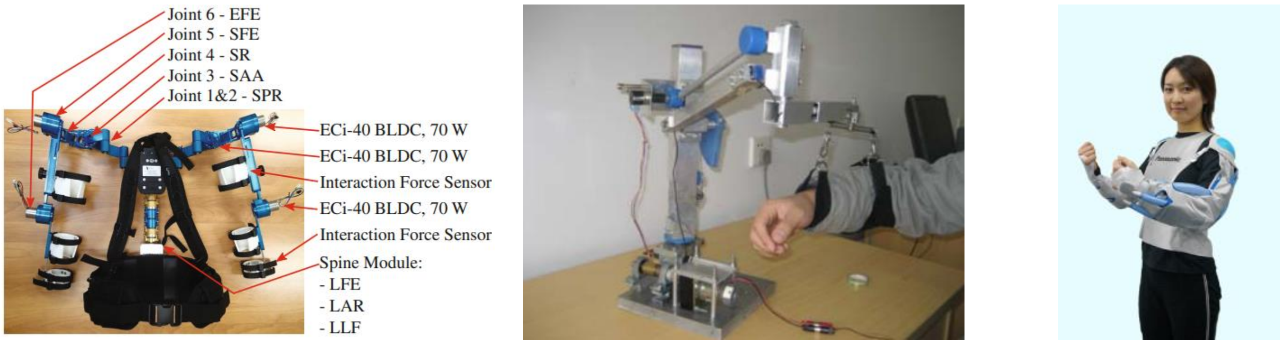


FIGURE 4. **Upper limb assistive device concept.**

Currently, there are various assistive exoskeletons available which can be used for elderly assistive purposes during their ADL. One example of such upper limb assistive device for elderly called as ASSIST has been proposed by Sasaki *et al.* [36]. It has a lightweight structure which has 1 DOF assisting the wrist flexion and extension motions. The validity and effectiveness of the proposed device has been demonstrated with the experiments. In general, ASSIST can reduce the muscle fatigue and provide additional torque for limbs to complete the specified motion trajectory (Table 1).

Recently, a device named AXO-SUIT has been developed for older people, so they can perform ADL. It consists of lower-body and upper-body prototypes (LB-AXO and UB-AXO respectively) [37, 38]. The upper limb part depicted in Figure 5 (a) possesses exoskeletons for both right and left hands, where each has 3 active and 3 passive DOFs interconnected in between with 1 spine module. The force sensors distributed along upper limbs are used to establish interaction between the user and the robot. Currently, the product is in a research stage development and various experiments are being conducted with human subjects to test and demonstrate its validity and effectiveness.



(a) (b) (c)

FIGURE 5. **(a) Upper limb exoskeleton from AXO-SUIT project. (b) Assistive device to support vertical motion. (c) Power Jacket Realive.**

In the other work, Gu has proposed a mechanical device as shown in Figure 5 (b), which allows elderly to continue maintaining independent lifestyle [39]. The mechanical device helps users in different actions like self-feeding, working on a computer and drawing pictures by themselves. DC motor is utlizied to activate parallel mechanism through the usage of strings. Force sensor was used to track assistive torque exerted to the subject's arm. The stiffness of a specific muscle was observed with the employment of tactile sensors. The reliability, safety and usage friendliness of the system is obtained with the application of sensor measuring stiffness level of the muscle. In addition, it is easy to attach and fix stiffness sensors. The skin condition does not affect the signal extraction which means that it can properly extract muscle contractions even with clothes in between. The system is mainly made from aluminum alloy together with other compositions. There are also some other meal feeding assistive devices for elderly, however such assistive devices have no effect on conducing people's involvement in that process [40, 41].

Soft exoskeleton for upper limb assistance, Power Jacket shown in Figure 5 (c) from Panasonic- Matsiushita Electric Industrial was constructed for stroke survivors who are incapable to move their limbs [42]. Such device is also applicable for assisting elderly people with weak movement abilities. The exoskeleton is embedded with 8 air muscles that extend or flex using compressed air. Myomo, *Inc*. has developed several type of assistive robotic upper limb exoskeletons. One such product that can be used by elderly for performing ADL is called as MyoPro for Veterans shown in Figure 6 (a). This product is commercially available [43, 44]. The system enables people to continue doing their hobbies like woodworking, cutting food, preparing meals. Muscle contractions are detected using electromyography (EMG) sensors installed in the system.

(a) (b)

FIGURE 6. **(a) MyoPro exoskeleton for Veterans. (b) HAL for living support.**

Cyberdyne Inc. developed various type for exoskeletons both for lower and upper limbs. One of its commercially available upper limb single joint exoskeleton named HAL in Figure 6 (b). HAL uses brain nerves to send various signals to muscles for the control of exoskeleton [45]. A low cost 2 DoF upper limb device design has been proposed by Mohamed *et al*. [46]. The device has two usage options. In the first option, device is worn on a subject making it portable and in the second one, it can be attached to the cart to reduce the load exerted on a user as shown in Figure 8. Inertial Measurement Unit (IMU) sensor has been used to take measurements of user arm's joint angles. Potentiometer is used for measuring robot angles. The mechanism employs PID control and actuates using Worm Drive motor.

(a) (b)

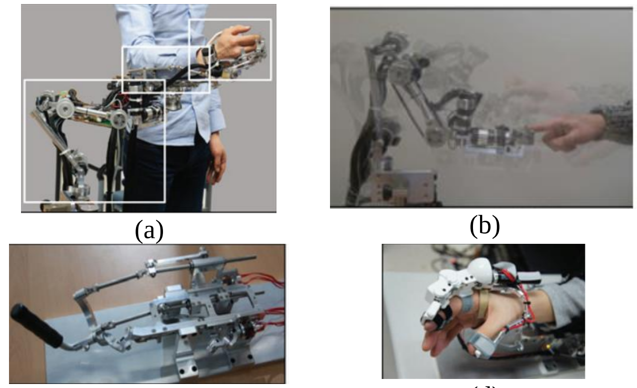
FIGURE 7. **(a) Portable mode. (b) cart fixed mode of 2 DoF upper limb exoskeleton.**

A 6 DoF robot based upper limb structure CABexo which is driven by cables has been described in the work by Xiao *et al*. [47]. CABexo is based on epicyclic gear trains allowing to satisfy the movement needs of elderly. The upper limb mechanism proposed in the research work by Ieki *et al*. in Figure 9 was designed to assist elderly during ADL [48]. It allowed to improve the usage of wheelchair for handicapped elderly by incorporating self-active cast which implies low energy driving system for residual function translation to the upper limb part. Pressure and EMG sensors are employed in the control unit to establish sensory feedback.

FIGURE 8. **Usage of exoskeleton while active cast.**

Latt *et al.*, have proposed the 7DoF exoskeleton named “Spexo” which supports elderly in carrying out various ADL such as drinking, eating and hair combing. Moreover, other than assistive actions, it may also be used for the rehabilitation purposes [49]. The system is actuated with the use of DC motors. It should be noted that during the design stage it is decisive to consider the different physical proportions of human body, therefore the mechanism has telescopic features which can fit people of different sizes. Moreover, Microsoft Kinect is applied to recognize the food plate location and direct the exoskeleton towards the specified position.

Upper-Limb exoskeleton (KULEX) has been proposed which is dedicated for assisting older and disabled people during ADL [50]. The proposed system includes 3 sections as shown in Figure 10; 1-DoF hand part for assisting grasping motion, 6-DoF serial robot for supporting forearm movement and 3-DoF parallel mechanism for assisting wrist movement, moreover the overall structure consumes less power, has sufficient maneuverability and a light weight.



(c) (d)

FIGURE 9. **(a) Overall system of 10-DoF upper limb exoskeleton KULEX. (b) forearm support part. (c) 3-DoF wrist part. (d) grasping part.**

Novel design of 7-DoF power assisting device for upper limb has been proposed after measuring the joint motions of human shoulder in the work by Kiguchi *et al.* [51]. Actuation is implemented with the use of 7 DC motors, moreover springs allowed to decrease the load of motors during shoulder joint movement. The potentiometer was embedded on board to measure the extension and flexion of shoulder joint angles. The control part is based on EMG signals, whose features have been extracted by calculating its RMS values. To determine whether power-assist function is appropriate 3-axis force sensors were employed.

A. Actuation

The selection of appropriate actuators for the upper limb exoskeleton is a significant aspect which developers should take into consideration during design and construction stages. Actuators can supply required torque to specified joints to help subjects in their limbs’ movement. They are usually evaluated and chosen based on their characteristics in terms of their weight, power, precision and size. Type of actuation is the key element in the provision of portable feature for exoskeleton. The actuators utilized for the design of these upper limb robotic exoskeletons can be categorized in the traditional electromagnetic based actuators and the later development in the form of compliant actuators. The portability is a very important factor among assistive exoskeletons which are used for ADL. Different types of actuation systems are employed among upper limb assistive mechanisms such as electric, hydraulic, pneumatic and Bowden cable-based actuator mechanisms. Each of these types has its own benefits and drawbacks. The benefits and drawbacks of each type of actuation for exoskeletons are thoroughly described in the works [52-55]. The summary of advantages and drawbacks of 3 main actuation types is also presented in Table 2.

Table 2. General summary of advantages and drawbacks of each actuation type

Actuation type	Advantages	Drawbacks
Electric	*Highest precision for position control *High repeatability *Smooth functioning *Silent operation *Easy to program	*Expensive price *May overheat *Large size and weight
Pneumatic	*Easy to operate and install *Low price *Light weight *High repeatability *Good accuracy *Safe operation *Applicable in harsh weather conditions and environments *Safe operation	*Lower efficiency *Presence of compressed air source-increases price *Not simple to build for complex projects, presence of valves and pressure control is required
Hydraulic	*Larger torque *Larger power to weight ratio *Constant force	*Fluid leakage *Lots of parts are required to operate (pumps, valves, etc)

Majority of covered assistive exoskeletons which can be worn and used by elderly use electric motors to drive the system and few of them used pneumatic air muscles. Details of the actuation for each device is presented in Table 1. Although electric actuation has high torque and precision, it is heavier than the other types. There is also another class of actuation called series elastic actuators, which are capable to increase the stiffness of the system. Such actuation has been implemented in motorized 4 DOF upper limb exoskeleton named WREX [56]. Series elastic actuators supply necessary torque and make users feel comfortable while wearing exoskeleton. Hofmann *et al*., have proposed the mechanism which uses Bowden cable to remotely activate the movement of upper limb extremities, the results reveal that the proposed mechanism is dust and water proof, has sufficient power to move the limbs and has a compact and compliant design [57]. Such systems do not require accurate alignment of the joints of human and exoskeleton [58]. Moreover, the battery and actuation systems are placed remotely, reducing the pressure on the upper limb extremities. Randazzo *et al*., have introduced wearable hand exoskeleton Mano shown in Figure 11 which is dedicated towards assisting in performing various ADL and can also be used for recovery of sensorimotor functions [59]. The system employs Bowden cables to transmit the motion for grasping performance.

FIGURE 10. **Hand exoskeleton Mano.**

Another soft upper limb exoskeleton named Exosleeve (Figure 12) is proposed in the work by Natividad *et. al*. and assists shoulder abduction and adduction motions [60]. The device has a pneumatic actuation and allows to fit people with different anthropomorphic parameters. The results of experiments involving healthy subjects demonstrated that this device is able to reduce the user's muscle activity enabling to delay the fatigue and also allowing people with motor impairments to perform desired limb movements.

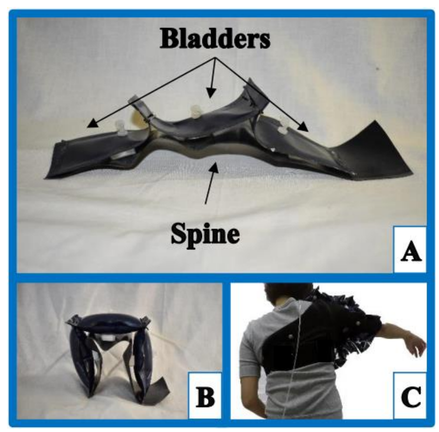


FIGURE 11. **Upper limb exoskeleton Exosleeve.**

B. *Sensors*

Sensor play an important role in the development of mechanism as well as control of the upper limb robotic exoskeletons. The role of these sensors is categorized in two classes; first one relates to the control of robot applied forces to the upper limb and second one is related to the estimation of human user intent. This first class is required to establish closed loop feedback control system for the upper limb exoskeletons and provide essential interaction between upper limbs of subject and the device itself with the proper selection and application of sensors. The first class involves sensors such as encoders for control of displacement and velocity, load cells for the control of forces and pressure transducers for the control of pressure in case of pneumatic and hydraulic actuators. The second class of sensors are utilized to measure the intent of human user of human-robot interaction. Sensors such as load cells, EMG and EEG based Brain-Computer Interfaced sensing systems are utilized for that purpose. A description of sensing systems used for each of the upper limb exoskeletons is described in Section III along with the mechanism details. However, a brief description is provided below to enhance the readability of this paper.

Force sensitive resistors were used in 3-DoF robotic exoskeleton which is intended both for assistive and rehabilitation purposes of the upper limb in the work by Huo *et al*. [61]**.** The general method of implementing assistive feature in exoskeletons is determining the amount of joint torque required to realize the desired limb movement and providing partial or full power to the subjects through the mechanism actuation [62, 63]. The implementation of EMG based control does not require calculation of the of human limbs' dynamic model.[64]. Using synthesized EMG signals for the feedback system in the upper limb exoskeleton has improved its performance in terms of increasing the exoskeleton mechanical gain [65].

Although EMG and force sensors are used quite often, in some cases they may not accurately represent the movement intentions of elderly either due to tremors or when the limbs are completely paralyzed. Therefore, Lalitharatne *et al*., have proposed a method, where electroencephalography (EEG) signals are used to decode the motion characteristics of upper limbs [66]. Specifically, the work applies genetic algorithm (GA) for model training and the outcome of the work suggests that EEG signals can be applied into decoding the velocity of elbow joint.

The interaction feedback between user and exoskeleton can be improved with the integration of sensors which are capable to extract the limb motions [67]. The motion trajectories of human limbs can be obtained with the application of IMU sensors, which incorporate accelerometer, gyroscope and magnetometer [68]. IMU and potentiometer sensors have been used to establish the interaction between 2 DOF upper limb exoskeleton and the subject to obtain comfortable and compliant joint motions in the work done by Atia *et al*., [69]. As a result, high performance of the device has been achieved in terms of successfully following and controlling upper limb motions.

TABLE 1. EXISTING UPPER LIMB EXOSKELETONS FOR ASSISTIVE PURPOSES OF ELDERLY AND WEAK PEOPLE

№	Name	Application Domain	Degrees-of-Freedom	Actuation Type	Control Strategy	Sensors
1	Active A-gear (2016) [70]	Support arm function for adults with Duchenne muscular dystrophy (DMD) in ADL (Laboratory prototype)	5- DoF	Brushless DC motor together with planetary gearboxes	Admittance control with force based interface	6 DoF force/torque sensor, hall sensors
2	Power-Assist Exoskeleton (2012) [71]	Assist physically weak people in daily life movements (fixed on wheelchair) (Laboratory prototype)	7- DoF	7 DC motors	Electromyograph (EMG)-based impedance control	Encoders and potentiometers, force/torque sensors
3	CABexo (2017) [47]	Assist elderly people and disabled people in ADL (Software model stage)	6- DoF	DC motors (cable-driven systems)	Not introduced yet	Not introduced yet
4	Serial-Parallel Exoskeleton (2011) [72]	Assist Elderly/ Physically Disabled people in ADL, mounted on wheelchair, (Laboratory prototype)	7- DoF	The Kollmorgen brushless DC motor, Faulhaber motors	Admittance control	Force/torque sensors
5	Low Cost Upper-Limb Exo [73]	Assist elderly people (Laboratory prototype)	2- DoF	Worm Gear Motor ZD1735	PID controller	IMU sensors
6	Upper-Limb Powered Exoskeleton (2007) [74] [75]	Assistive/Therapeutic for ADL (Laboratory prototype)	7- DoF	DC brushed motors	Neural-controlled (Myoprocessors)	Potentiometer, shaft encoder,Force/torque sensors
7	Portable Assistive Arm Exoskeleton (2012) [76]	Assistance/Stroke Rehabilitation (Laboratory prototype)	1- DoF	DC motors, planetary gear motors	Brain computer interface control	EEG, EMG encoders and potentiometers
8	Myosignal-Based Powered Exoskeleton (2001) [65]	Assistive, focus on the development of HMI control (Laboratory prototype)	1- DoF	DC servo motor with a planetary gearbox	Moment-based control system with embedded myoprocessor	Encoders and potentiometers, EMG sensor
9	Gopura and Kiguchi [77]	Power assist during ADL for physically weak people	7- DoF	DC servo motors	EMG – based impedance control method	Force/Torque sensors, potentiometers, encoders
10	MULOS [78]	Assist people with limb weakness or disability, attached on wheelchair (Laboratory prototype)	5-DoF	Electric motor and cable drives	PID control	Encoders
11	IKerlan's Othosis [79]	Augment physical performance of daily tasks, wheelchair mountable (Laboratory prototype)	5-DoF	DC motors and Festo pneumatic muscles	PID control	Festo torque sensors

12	ETS-MARSE [80]	Assist in daily upper limb movements and rehabilitation (Laboratory prototype)	7-DOF	Brushless DC motors	"Sliding Mode Control" Technique and computed torque control	Potentiometers
13	Naidu [81]	Assist disabled and weak people in ADL (Software model)	7 DOF	DC motors	Feedback control	Encoder
14	Sasaki [36]	Motion assist	1-DoF (Wrist)	McKibben type pneumatic muscle	Controled by Pressure control system	Encoders and potentiometers
15	Kobayashi & Hiramatsu [82]	Provide muscular support	6-DOF	McKibben type pneumatic muscle	Open loop control	Electropneumatic regulator (controls output of compressed air)
16	Ramos [83]	Complete task of lifting a payload	2 Passive – 1	Pneumatic Artificial Muscles (Hill-type muscle)	Control based on the method of GA (Genetic Algorithms) evaluate the chromosomes.	sEMG electrodes and potentiometers
17	RUPERT [84, 85]	Assistive/Rehabilitative	5-DOF Shoulder (2 -DoF, Wrist- 1DoF, Elbow - 2DoF	Pneumatic muscle actuators and FES stimulators	"Iterative learning controller-based feedforward controller and Closed-loop controller with a PID-based feedback controller"	–

C. Material

The material of exoskeletons is usually chosen based on strength to weight ratio. It influences the overall weight and the comfortability. Rigid structure can be provided by aluminum alloy, titanium or titanium alloy. Such type of materials can be used for assistive devices which are fixed on wheelchairs, so the weight of the system will not be exerted on human. For the portable ones which are worn to people who can walk, it is preferable to use composite materials like carbon fiber since they have lighter weight, but it is more difficult to reshape the material when comparing to metallic ones. Soft materials can also be used.

IV. Control

This section describes different types of control schemes implemented for the assistive upper limb exoskeletons which can be used by elderly people for their ADL. Control of the exoskeleton is another key element during the development stage. State of the art of control algorithms developed for different types of exoskeletons are presented in various works [14, 86-89]. The control of robotic upper limb exoskeletons can be categorized based on the type of control algorithm used and the type of activities assisted by using the control algorithm. The type of activities assisted by using these control algorithms are not explicitly provided in literature. For this review, the types of control algorithms developed for these upper limb robotic exoskeletons is discussed.

There are two main categories of control algorithms used for the upper limb robotic exoskeletons. The first category of control algorithms guides the upper limb of elderly people on pre-defined paths without considering the intent and participation of human subject. This category is known as trajectory tracking control in literature. The second category of control algorithms used the robotic sensors such as force, EMG and EEG to estimate the intent of human subject and modulate the robotic assistance accordingly. This category of control algorithms is referred to as Assist-as-Needed (AAN) in literature. The advantage of AAN control over conventional trajectory tracking control is that the human subjects' intent and muscular capabilities are estimated by using various sensors and the robotic assistance is customized to the individual needs of each subject. Whereas, in the trajectory tracking control system, the human subjects' upper limbs are guided on pre-defined paths without considering their muscular capabilities. Therefore, the modern and state-of-the-art upper limb assistive robotic exoskeletons are increasingly utilizing the concept of AAN control.

Hou and Kiguchi have proposed the AAN control algorithm with perception-assist function for upper limb device, which can be useful for people suffering from minor physical disabilities or elderly. This control algorithm helps them to move their upper limbs in a proper motion trajectory [90]. The core component of algorithm is lying behind the idea that the proper motion of the limb from starting point to end point is described within the boundaries of the virtual tunnel. In case, the limb motion trajectory goes beyond the boundaries of virtual tunnel, such movement is considered to be improper. The efficacy of this algorithm has been tested and verified using 7 DOF upper-limb assistive device by performing several sets of experiments. In order to help elderly in self-feeding tasks, Lei *et. al.* has proposed a method for 7 DOF exoskeleton which is based on AAN approach in the form of phase-dependent trajectory planning, where the feeding process is divided into several various subtasks or phases. Smooth and natural motion is ensured with usage of a redundancy resolution technique called "Sensorimotor Transformation Model (STM)" [91].

Another common problem which elderly usually encounter is tremor [92, 93]. Specifically, tremors are common disorders which usually occur in the upper extremities. Tremor is considered to be the periodic unintentional motions of different body parts which causes discomfort in performing ADL such as water drinking, handling some objects while eating, writing and the others [94, 95]. Usual EMG based, AAN control implemented in exoskeletons may receive wrong input commands due to tremor and therefore generate erroneous motions. Therefore, Kiguchi *et al.*, have developed an AAN control method for a 7 DOF upper limb assistive exoskeleton which suppresses tremor [96]. The vibration due to tremor is reduced by the application of the pseudo-inverse matrix's null space together with the location of hand and tool. Moreover, by conducting set of experiments the effectiveness and feasibility of the proposed tremor suppression control method has been verified. Hayashi *et al.*, has proposed an AAN control algorithm based on torque optimization control method for 7-DoF upper limb exoskeleton which comprehends human elbow movement intention through the application of pseudo-inverse matrix's null space [97].

In order to provide precise movement tracking of an exoskeleton, usual trajectory tracking control laws need larger output impedance. Also, controlling the trajectory of the joint results in the stiffness of an exoskeleton [98]. Impedance control cause users to feel less inertial forces during the usage of assistive exoskeletons by providing required assist-as-needed motions and allowing exoskeletons to actively follow human movements [99-101]. EMG based AAN impedance control was integrated in the 7 DOF upper limb assistive exoskeleton (presented in Table 1) by Kiguchi *et al*. The experimental results suggest that this approach can be adapted to any user [71]. The drawback of impedance control is that it can affect the system stability when the mechanical impedance value is large [102].

A 7 DOF upper limb exoskeleton named SUEFUL-7 has utilized an AAN impedance-based control which helps to simulate and generate the upper limb movement anatomical trajectory. The impedance control is used in conjunction with muscle model oriented control approach [77, 103]. Other technical parameters for SUEFUL-7 are presented in Table 1. AAN algorithms based on admittance control methodology is applied to drive 3 DC motors in the upper limb exoskeleton developed by Huo *et al*. The proposed system was examined on healthy individuals and the model for detecting movement intentions of the user has been also incorporated [61]. In the work done by Ivanova *et al*., assistive 7 DOF upper limb exoskeleton has been introduced [72]. The system is mounted on wheelchair and intended to support shoulder, elbow and wrist movements of elderly population. Application of admittance control algorithm in the mechanism allowed to reach high maneuverability like anatomical upper limb motion of the human.

The conventional trajectory tracking control algorithm developed for the upper limb assistive robots has a standard architecture. It utilizes a proportional-derivate (PD) or proportional-derivative-integral (PID) control law to guide the human limb on predefined trajectories without considering the intent of user. All these trajectory tracking control algorithms based on PD and PID control laws developed for these upper limb assistive exoskeletons summarized in Table 1.

V. Discussion and Future Prospective

Majority of elderly people are experiencing restricted movement abilities in their upper limbs, which brings challenges and difficulties in the performance of usual ADL like; dressing, self-feeding, self- caring and other housework activities. In order to promote good quality of life for ageing population, automated solutions should be realized in terms of wearable robotics, which will allow elderly people to stay independent. Due to the muscle deterioration which happens with ageing, upper limb robotic exoskeletons can be helpful in performing various movement tasks such as handling, moving, carrying and holding different things. This paper presents comprehensive review of currently existing assistive robotic exoskeletons for upper limb which can be used by older group of people. Moreover, the technological insight in terms of DOFs, actuation type, embedded sensors, control architecture and type of assistive motions they provide has been thoroughly described. Majority of currently existing robotic upper limb exoskeletons are dwelling in research and development and have not entered the commercialization phase. Moreover, the majority of presented assistive systems are bulky, heavy and are not designed for practical usage during the daily life activities at home. Taking into consideration that target group who needs assistive devices are weak and having physical capability problems, heavy exoskeletons may cause faster muscle fatigue. In order to reduce the weight exerted on the upper limb by these exoskeletons, batteries and actuation systems can be placed proximally. Thus, demanding remote actuation, which can be realized through the application of Bowden cables, hydraulic or pneumatic type of actuation.

Recently significant attention is given to the development of soft exoskeletons which involve innovative textiles making them more user friendly and convenient to be used. Improvement in motion of upper limbs for holding and grasping tasks can be realized through such devices. In comparison to usual hard exoskeletons, soft ones have many benefits over the hard exoskeletons, such as light weight, ability to wear and interaction with clothes, making it less visible. Soft ones can be produced in different sizes considering people with different anthropomorphic sizes. In addition, they do not have constraints on joints due to the non-rigid structure. Therefore, interference with natural body motions will be more compliant. The actuation system of soft robots is inspired from the biological muscle movements. Both cable-driven electromechanical actuators and pneumatic ones have demonstrated their ability to have positive impact on the limbs' movement assistance. Due to the lower weight and size, less energy will be needed to run the system. Undoubtedly, the soft exoskeletons can provide assistive torques, however, such devices also possess some drawbacks. Since, they do not have rigid structure, the battery and actuation placement can be problematic.

The development of control systems for these upper limb assistive exoskeletons also present significant challenges in the form of providing customized assistance depending on the needs of individual human subject. The sensing mechanisms utilized for the development of these control systems are not capable enough to determine the intent and required level of assistance of human subject. Consequently, the robot provided assistance is not adapted fast enough in real time, which may result in unwanted motions of the human subject in the form of collisions. There is a strong need to develop the sensing systems and accompanying control algorithms which are capable enough to estimate and adapt the amount of robotic assistance required in real time. This will further enhance the utility and acceptability of the robotic upper limb assistive exoskeletons among the ageing population.

Currently, the field related to the development of assistive wearable robots for elderly to perform ADL is in high demand, and it is subject to increase with the growth of elderly population around the world. It is essential for governments and various research groups to invest into such projects related to the construction and integration of such devices. The further development of this field will have far reaching socio-economic benefits.

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