UPPER EXTREMITY ROBOTICS EXOSKELETON: APPLICATION, STRUCTURE AND ACTUATION

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ABSTRACT

Robotic exoskeleton is getting important to human in many aspects such as power assist, muscle training, regain motor function and rehabilitation. The research and development towards these functions are expected to be combined and integrated with the human intelligent and machine power, eventually becoming another generation of robot which will enhance the machine intelligent and human power. This paper reviews the upper extremity exoskeleton with different functions, actuators and degree of freedom (DOF). Among the functions, rehabilitation and power assist have been highlighted while pneumatic actuator, pneumatic muscle, motor and hydraulic actuator are presented under the categories of actuator. In addition, the structure of exoskeleton is separated by its DOF in terms of shoulder, elbow, wrist and hand.

KEYWORDS

Exoskeleton, Power-assist, Rehabilitation and Upper extremity

1. INTRODUCTION

A robotic exoskeleton is a system developed to assist those physically weak people to regain their power or give augmentation power to normal people. An exoskeleton is first used to describe the external skeleton of animal which playing the roles of protection, excretion, sensing, support and defense [1]. The advantages of its rigidity and protective is then mimicked and utilized by human to develop armor suit, orthotics and prosthetics. According to Nef *et al.* [2], the robot exoskeletons are either end-effector robots or exoskeleton robots. End-effector is only connected to the user or patient at one point of the forearm which is determined to have a better guidance of arm motion with its simpler design. However, it cannot exert torque to the user joint so the exoskeleton has an advantage compared to the end-effector robot. In exoskeleton, the torque at each joint is controlled separately. Therefore, the hypertension to limb or joint can be avoided.

At recent decades, advanced technology has make improvement on robotics exoskeleton and a lot of researches have been made such as Berkeley lower extremity exoskeleton (BLEEX), Hybrid Assistive Limb (HAL), Anatomically Correct Testbed (ACT), MIT-MANUS, PUMA (MIME), PHANTOM, WAM Lokomat and etc. [3]. In the researches, the developed robotic exoskeletons transmit power to the human joint through different kind of actuators. The integration of human intelligence and machine power undoubtedly is a milestone to increase the human power and intelligence of robots. Since many robotics exoskeletons have been developed, there is a need to categorize them by using different criteria. In term of functionality, they can be categorized into power-assist, rehabilitation, tele-operation and haptic interaction in virtual reality. In term of exoskeleton structure, they can be categorized into three types as upper extremity, lower extremity and full body [4]. In addition, the actuator of exoskeleton can be categorized into motor, pneumatic actuator, hydraulic actuator and hybrid.

Power assist exoskeleton gives extra or additional strength to normal people in order to make them able to do extreme work. Rehabilitation exoskeleton helps physically weak people such as patient after stroke to regain their power. A tele-operation exoskeleton is a system which allows users to control a robot at distant and virtually by using their hand instead of using a joystick. Light exoskeleton is an exoskeleton based haptic interface for human, it is designed to be wearable and capable of providing controllable force so it is suitable for the applications where both motion tracking and force feedback are required [5]. Upper extremity exoskeleton includes mechanical structure on the shoulder joint, elbow joint and wrist joint. While a lower extremity exoskeleton includes the structure of ankle joint, knee joint and hip. Finally, the full body exoskeletons include the upper extremity and lower extremity exoskeleton.

The lower extremity exoskeleton has been reviewed by the authors [6], so this paper only focuses on the research of upper extremity exoskeleton. It reviews the applications, type of actuators, mechanical structure and the controlling methods. The applications of exoskeleton are first identified in section 2. Then the structure of exoskeleton is discussed in section 3. The various types of actuator are presented in section 4.

2. APPLICATION OF EXOSKELETON

There are a few applications of exoskeleton but this paper only reviews the rehabilitation exoskeleton and power assist exoskeleton.

2.1. Rehabilitation

According to Caldwell *et al.* [7], there are over 700,000 people in US and over 65,000 people in UK survive a stroke every year. Among these survivors, some suffer from chronic hemiparesis. They should receive intensive care and physical therapy to encourage their motor recovery. However, due to economic pressure, non-life threatening and labour intensive, many patients do not receive enough or any physical therapy before going home. In order to help these patients, researches have put their effort in developing robotic rehabilitation system to allow the patient exercise in-home physical therapy. The first assistive device was begun at 1960 and followed by the studies of ARM Guide, Gentle-s, MIME, MIT-Manus, and Rutgers Master II-ND. It is very obvious that there is a demand for the rehabilitation robot and the technique in the development.

An exoskeleton for forearm pronation and supination rehabilitation has been presented by Andreasen *et al.*[8]. The developed system is expected to improve the neurological recovery and promote the function used of upper extremity through an effort of repeated motor practice. The authors have set their goal clearly in helping those neurological impairment patients in the development of a computer assists and user interactive orthosis that capable to provide movement recovery training. Secondly, they aimed to develop a program which can represent patient movement involved in activity of daily lives (ADL). Because of the forearm recovery exercises only involve pronation and supination, therefore the structure attaches and fixes the patient forearm that allows the elbow joint and wrist joint to move freely. The motion torque is provided by the motor. Sensors are implemented in the actuator to give position feedback to the system in order to adjust the motor torque. Then, the actuator will perform the action as (i) the motion of the pronator quadrates and pronator teres during pronation and (ii) the motion of biceps and supinator

during supination. After the training of muscle, patients are expected to recover their forearm motion.
Crocher *et al.* [9] explored the programmable of upper extremity exoskeleton in impose certain joint coordination patterns during rehabilitation. Due to the conventional rehabilitation for upper limb involves the interaction with both upper arm and lower arm, it is expected that the robotic rehabilitation exoskeleton can cover both the end-point control and inter-joint synchronization. An ABLE exoskeleton has been employed in their study. The exoskeleton has 4 DOF which are actuated by motors and its power transmitted by cable. Optical incremental encoders were installed at each joint to enable the calculation of joint position and corresponding speeds by derivative method. In addition, a velocity synergy based controller was developed which modifies the position of the active movement of the user. Besides, the developed system is able to characterize both active patient motion as well as passive (therapy assisted) motions. Seven hemi paresis patients volunteered in the conducted experiments of the system. The exoskeleton attached to the subject at the bicep level and wrist. The subject was then asked to perform several actions so that the movement can be recorded to perform data analysis. The second objective of the experiment was to study the capacity of the controller to change the joint coordination with giving small effect to the hand during a movement. The conducted experiment showed that the exoskeleton is able to change the upper limb coordination patterns of hemi paretic patients without modification of end effectors kinematics.

Bonato *et al.* [10] developed an advanced rehabilitation robot (RehaBot) which can provide training of different ambulatory tasks to patients besides reduce the workload of physical therapists. This system can be run under direct monitoring or at remote site through telepresence operation control. To developed system has complied Series Elastic Actuator (SEA) technology in order to acquire a safe and reliable control capacity. This system provides both upper and lower limb rehabilitation, however they are run independently. The configuration to run both rehabilitations is not yet completed. The upper extremity cover 7 DOF meanwhile 4 DOF at the lower extremity. The control layer of this system includes gait control, feedback from patient and remote control. The gait control is used to guide the walking of the patient. For the feedback control, sensors are installed at the structure and attached to the patients to improve the rehabilitation motion and to monitor the patients' emotion. Finally, the remote control allows remote supervision. This system is commented as user friendly and safe due to its remote controllable and the built in SEA technology.

Bergamasco, *et al.* [11] presented the design of an upper extremity rehabilitation exoskeleton, L-Exos system. The L-exos is a force feedback system for the human arm which is unique with its high performance, low inertia, high payload to weight ratio and back-drivability. It is designed to be wearable and capable to provide a controllable force at the center of user hand. The structure covers the shoulder, elbow and wrist. However, the system is redundant when motor compensation is performed to the patients. Overall, the reachable workspace of the system corresponds to 70% of a normal person reachable workspace. To test the functionality of the system, three tasks have been performed by (i) a reaching task, (ii) a free motion task and (iii) an object manipulation task. The result indicated that the system does not influence the motion of patient and causes incorrect motion. In addition, the motor compensation makes the robot exert no force on the patient so it is a suitable tool to allow patient to have rehabilitation.

2.2. Power Assist

The technology of robotic exoskeleton not only benefits patients for rehabilitation, it also assists human in power augmenting or burden reducing. The first powered exoskeleton was an exoskeleton suit co-developed by General Electric and the US Military named Hardiman. It was used to amplify the strength of soldier in order to carry heavy weapons, tools and equipment. However the suit was an incomplete product because it cannot be powered up even with human inside. But it has highlighted the challenges and triggered the further development of exoskeleton. Until recently, some successful products of powered exoskeleton are introduced such as Berkeley Exoskeleton (BLEEX), Sarcos Exoskeleton and MIT Exoskeleton [12]. The technology in power augmenting exoskeleton is getting mature and further developments are expected to benefit human. Choi *et al.* (2012) [13] designed a wearable upper extremity exoskeleton that is capable to lift heavy thing which the load is distributed to the exoskeleton and human in a proper manner. The robot is a whole body exoskeleton which comprises of upper extremity and lower extremity. Their simulation result indicated that the burden of human in carrying heavy object can be reduced by the exoskeleton with proper load distribution.

Chen *et al.* [14] developed an exoskeleton to train the user muscles strength instead of helping the user in lifting objects. Conventional muscle training device uses weight stacks to produce resistance which is possible to cause injury to the user from the inertia generated. To overcome this problem, the authors proposed an unpowered upper extremity exoskeleton to train the upper limb muscle. The exoskeleton has 3 DOF at the shoulder and 1 DOF at the elbow that enables muscle training of motion of internal-external, abduction–adduction, flexion-extension at the upper arm and flexion–extension at lower arm. The resistance is generated by the arrangement of spring that installed at the exoskeleton. Since the spring produces low inertia, the user has a lower risk of sports injury. The experiment result indicated that a linear relationship between the external load and spring. So it is suitable to use spring to replace the weight stack in a muscle training device.

Hyodo *et al.* [15] presented a wearable full body exoskeleton which potentially to be used in power augmenting and rehabilitation. The authors implemented sensorless torque detection and its control system in the full body suit. Thus, the torque control of the exoskeleton can be carried out without the requirement of sensing unit. The functionality of the sensorless system has been tested in a developed prototype. The link length of the structure can be adjusted to different users. In addition, the control of system is based on the Electromyography (EMG) signal acquired from users. Weight lifting and upholding test were conducted by subject wearing of the exoskeleton. The results showed that the method is workable and efficient.

3. MECHANICAL STRUCTURE

Upper extremity of human can be categorized into upper arm and forearm while the links involved includes shoulder joint, elbow joint and wrist joint. Different parts of upper extremity corresponding to the exoskeleton has been developed for the purposes of muscle training or rehabilitation such as wrist joint exoskeleton [16], shoulder joint exoskeleton [2], elbow joint exoskeleton [17], the upper limb exoskeleton [18] and hand [19].

3.1. Wrist Joint

According to Lee *et al.* [16], the conventional exoskeleton system on the forearm and wrist part focuses less on degree of freedom, range of motion and output torque capability. So the authors have proposed a forearm and wrist rehabilitation exoskeleton, RiceWrist-S which has a better range of motion and degree of freedom. The proposed forearm exoskeleton has 3 DOF including the forearm, wrist flexion-extension and wrist radial-ulnar. The user arm is attached to the skeleton and fixed by strip at the wrist and forearm. For safety purpose, an emergency stop mechanism has been implemented. The torque required will be produced by two DC motor actuator and cable transmission for the whole system. This cable transmission makes the RiceWrist-S a better candidate for virtual reality configuration compared to other wrist exoskeletons that using gear transmission.

3.2. Shoulder Joint

Accordingly to Nef *et al.* [2], shoulder joint is the most complex joint among human joints. Thus, the control and actuation of a shoulder joint is very challenging and complex. Unlike other joints such as elbow and wrist have simple rotation along their axis, the center of the rotation of a shoulder will be changed. Oversimplification in the design of the shoulder robot will result of misalignment between human and robot. The authors described the motion of shoulder and its corresponding actuation mechanism. The robots used were ARMin II and ARMin III which have 3 DOF about the shoulder. The ARMin II provides linear motion on the center of Glenohumeral Joint (CGH) while the ARMin III provides circular motion of the CGH. The ARMin II is relatively complex compared to the ARMin III due to its mechanical design. In addition, ARMin III is weight compensated by utilizing spring in the system. To enhance the safety, the system is equipped with a mechanical stop function. Finally, the test subjects of ARMin associated functions of the system. Nevertheless, some of the users found that no difference with the skeleton attached.

Most of the existing exoskeletons are having a similar structural frame in term of articulated rigid links regardless of the application of the exoskeleton. However, rigid link might not suitable to be used in certain application which emphasizes on the comfort of user or low torque requirement. Such application includes the rehabilitation robot where low torques, ergonomics and comfortability are important. In this situation, additional of a compliant component will have a better result. Qiu *et al*. [20] proposed an upper arm rehabilitation exoskeleton by using an alternate continuum mechanism. The main goal was to build a light weight and ergonomic rehabilitation exoskeleton. However, the development of this technique is not completed yet. So, they have built a preliminary prototype to study the continuum mechanism. Besides, kinematics of the mechanism and a hydraulic transmission design are studied. Unlike other exoskeletons, this mechanism provides 2 DOF to the shoulder joint instead of 3 DOF. Its structure consists of an end-disk, a primary backbone and a few secondary backbones. The bending of the exoskeleton is done by pushing and pulling the secondary exoskeleton simultaneously. The actuating of the continuum in turn orients the wearer's upper arm accordingly. As mentioned before, this mechanism still has some room of improvement such as mechanical component and its control system.

3.3. Elbow Joint

Chen *et al.* [17] has presented a wearable elbow exoskeleton with curved pneumatic muscle actuator (PMA). Since, elbow has only 1 DOF, so the prototype also actuate in one DOF. The system comprises of two PMAs which work in pair to produce torque required by the flexion and extension of elbow. The PMA provides several advantages such as non-linear torque, low-cost, clean and high power-weight ratio. Furthermore, the system implemented a hybrid fuzzy control strategy to control the nonlinear curved PMA and other pneumatic components. The performance of the system was proven through the experiments.

3.4. Hand

Human hand is a complex part to be mimicked by exoskeleton. However, researches in mimicking human hand mechanism have been found but there are room to be improved. Unlike the conventional industrial gripper, a commercial prosthetic hand comprises of grippers with a few DOF which are actuated separately. This kind of hand exoskeleton is simple but it is robust enough. It has the problem of reduced sensitivity and functionality [19]. Therefore, further development on ergonometric hand exoskeleton with DOF optimization is expected.

Patient who recovers after stroke needs rehabilitation to regain their hand movement. In addition, patient undergo physical therapy of bilateral movement instead of unilateral motion has better improvement in function recover. Jumailya *et al.* [21] aimed to design a post stroke rehabilitation exoskeleton system to help patient flex or extend their impair hand. The bilateral movement assistive device allows 15 DOF out of 21 DOF of the hand. The attachment of exoskeleton to the fingers through the Proximal Phalange (PP), Middle Phalange (MP) and Distal Phalange (DP), two supporting rods connect PP with MP another one connect PP and DP. Each rod is actuated by a motor, once the rod extend, the finger flex while contraction of rod cause the finger to extend. Since there are five fingers on a hand, five motors are required to actuate them separately. The system is covered inside a glove. It implants flex sensors inside that determines the fingers' position accurately. The research outcome indicated that the system is able to reach full flexion and extension for every finger. Finally, the several tests have been conducted to prove that the system has achieved their presetting goal.

Since 1960, thousands of motor driven rehabilitation devices have been developed due to its advantages of compactness, reliability and simplicity on recharging. However, the system becomes heavier when number of motors used increases. This problem becomes significant in the motor driven hand exoskeleton. Until recent, modern technology allows the development of hydraulic prosthetic hand which is safe, compact, controllable and simple. Thus hydraulic driven exoskeleton hands become competitive with motor driven one. Kargov *et al.* [22] presented an artificial hand with powerful miniaturized hydraulic system. Since the system implements myo-electrodes to sense the hand motion, it is recognized as an electro-hydraulic system which is known as hybrid system. Furthermore, the developed hand is very reliable and gives relatively large grasping force. Unlike other motor driven system, this artificial hand is preprogrammed for certain motion of hand and once signal is received through the myo-electrode, the control unit commands the hydraulic pump to actuate the robot finger.

3.5. Upper Limb

Bergamasco *et al.* [18] presented a whole upper limb rehabilitation exoskeleton. The proposed robot, RehabExos was an improved version of L-EXOS. They aimed to overcome the limitations of L-EXOS while remaining its effective features. The exoskeleton was based on a custom-designed actuator that ensures the performance of system safety, flexibility, joints' torque and etc. The exoskeleton has 5 DOF which includes the shoulder joint and elbow joint. The RehabExos is attached to the human at the middle of forearm and forearm level. The outcome of the research indicated that the RehabExos is relatively cheap, reliable and robust compared to the L-EXOS. Besides, it has a better performance in contact force control.

Similarly, Celik *et al.* [23] proposed an upper limb exoskeleton by referencing to an existing exoskeleton. The new exoskeleton named MAHI Exo II which was an improved version of MAHI Exo I. This rehabilitation exoskeleton has 5 DOF which enables the flexion-extension of elbow, pronation-supination of forearm, flexion-extension of forearm and redial-ulnar deviation. The robot exoskeleton has remained the basic kinematic structure of MAHI Exo I. But it demonstrated some improvement in terms of reduction of singularity and backlash, higher torque generation, capable to mount the system on the shoulder and smooth interchange between left and right arm configuration.

Balasubramanian *et al.* [24] presented a rehabilitation upper extremity exoskeleton, RUPERT IV. This exoskeleton has 5 DOF that includes the shoulder elevation, humeral external rotation, elbow flexion-extension, forearm pronation-supination and wrist flexion-extension. The system is actuated by PMA and controlled by a closed loop control system which comprises of PID-based feedback controller and ILC-based feed forward controller.

4. ACTUATOR

Among all exoskeletons, different types of actuator are used to actuate their system such as motor [25], pneumatic [26], pneumatic muscle [27], hydraulic [28] and even hybrid system [22].

4.1. Motor Actuator

Motor actuator has been employed in the robot of Moreau *et al.*[25]. It has a gravity compensation upper limb exoskeleton for rehabilitation. The structure of the exoskeleton consists of 4 links with 4 revolute joints. The 4 DOF included shoulder abduction-adduction, shoulder flexion-extension, shoulder internal-external rotation and elbow flexion-extension. These DOFs are actuated by brushless motors. The motors are used with the gear system to amplify its torque. The exoskeleton attached to the human arm that acquires signal through force sensors which implemented around the wrist and arm. These signals are then feedback to the control system to generate the appropriate signal to the motor which in turn compensate the weight of the exoskeleton. Thus, the user will feel no weight of the exoskeleton when moving his arm.

A rehabilitation exoskeleton, WREX robot developed by Agrawal *et al.*[29] has the similarity. WREX has 4 DOF where 2 of them located at the shoulder and 2 of them located at the elbow. The user arm is attached to the robot and the robot is controlled by residue force of the user. Its joints and links are actuated by brushed DC motor. In addition, there are connected with springs that forming series elastic actuators (SEA). SEA used in the system which creates accurate torque for the robot meanwhile provides softness to the user. It allows the user to raise their hand overhead and lift weight. It is controlled by a PI controller with velocity feedback that ensures the steady motor output.

Motor actuator and rigid link are used in the design of many exoskeletons. Nevertheless, it will make the system to become bulky and heavy at the rotational joint [30]. In order to reduce the mass of the system to the user, cable transmission is used in some exoskeleton design [31-32]. In the design, motors are located at the base frame instead of the robot joint. The exoskeleton is actuated by the motor and power transmitted to the joint by cable. These systems are more complex than those systems without cable transmission because the driven cable can only transmit forces to the joint and end-effector by tension. However, shorter setup time and exert zero static force on human arm are great advantages of rehabilitation exoskeleton.

4.2. Pneumatic Actuator

Many rehabilitation robots have been developed so far such as MIME and MIT-MANUS but none of them can provide sufficient power ergonometric to the user. This is a challenging issue since it is difficult to develop a robot with larger DOF with good dynamic range of motion and force. Bobrow *et al.* [26] try to overcome the problem by modifying and improving an existing exoskeleton, WREX. They combined the features of WREX, passive counterbalance with a pneumatic actuator and a non linear force control system. These counterbalance features allow the exoskeleton to actuate against gravity thus exert no force on user in steady state. In addition, the pneumatic actuator has higher power to weight ratio. Besides, the pneumatic actuator can remain the position of exoskeleton without spending energy because it is just the open or close of valve to control the pneumatic. Finally, the non linear control system allows the pneumatic actuator to control the position and it has the capability of active back drivability.

Pneumatic actuator is not commonly used in rehabilitation exoskeleton due to the difficulty in controlling. Hence, Bobrow *et al.* [33] addressed this issue and presented the development and control of pneumatically actuated exoskeleton, Pneu-Wrex. MEMs accelerometer is used in the control system to acquire the position and velocity of the exoskeleton. They put effort in ensuring the safety of the exoskeleton that includes the development of a few safety controls such as range of motion limits, pneumatic limits, software fault detection, etc.

4.3. Pneumatic Muscle

Common actuators used in robotic exoskeleton are rigid in structure, which work with speed reducer. Until the Pneumatic Muscle is introduced, “soft” robots have become an interest of researchers. The softness of pneumatic muscle excludes the system that use speed reducer, the actuator pair mimic the biceps and triceps of human arm perfectly [27]. A seven DOF upper extremity exoskeleton has been built by using pneumatic muscle [34]. Similarly, He *et al.*[35] developed a pneumatic muscle driven exoskeleton, RUPERT that is low cost and safe. The compliant actuator used in the system reduces the complexity of the robot control. Compared to the previous project, the difference is the actuator used in this system can actuate in two directions. Common Pneumatic muscle only produce pulling force so flexion and extension of arm need a pair of actuator. In this system, the actuator installed a spring inside so that it can actuate in both direction. The control of a pneumatic muscle is relatively simple but it is difficult to achieve excellent performance by using conventional control method. Chang [36] developed a control method, ASOFSMC which can reduce number of fuzzy and the experimental result indicated a good performance of the method.

4.4. Hydraulic Actuator

Bretthauer *et al.*[37] presented an elbow exoskeleton actuated by flexible fluidic actuator. The system also comprises of a hydraulic pump and a miniaturized pump. It is suitable to be fixed like mounting on a wheelchair compared to pneumatic actuator system. Another hydraulic actuated exoskeleton was presentated by Aalsma *et al.*[31]. Different from the formal exoskeleton, their system covered the upper limb instead of a working the elbow. However, they used a rotational hydro-elastic actuator (rHEAS) and symmetric spring to actuate the exoskeleton and give the system a stiffer admittance control.

5. CONCLUSIONS

The development of exoskeleton benefits the human which includes weaknesses or healthy people. In this paper, rehabilitation and power assist robots have been reviewed. The robotic exoskeleton can help physical weak or motor function reduced patient to regain their movement. In additional, it can help healthy people to train up their strength or to distribute out the weight gained by the users.

Pneumatic actuator, pneumatic muscle, motor actuator and hydraulic actuator are found to be commonly used in research study about actuator among exoskeletons. The motor actuator has the advantages of easy control and good accuracy while pneumatic actuator has the advantage of spend zero power in holding the position of robot. Furthermore, the pneumatic muscle mimics the human muscle perfectly while the hydraulic actuator gives high power output.

In the review, it is found that some researchers only focus on a single DOF at a single joint while some researchers look at the system design of whole upper extremity and even a few of the researchers carry out a whole body suit exoskeleton. No matter how many DOFs are included in the exoskeleton, their researches are benefiting human. Further review on the exoskeleton control system might help to understand more about the exoskeleton.

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