Low-extremity Soft Exoskeletons for Stroke Patients

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***Abstract*— Soft Exoskeletons are highly advancing in the recent robotic research. The key focus of this review paper is mainly on recent advances in soft robotics and the key challenges the field faces. It introduces concepts applicable to soft exoskeletons to the readers who are new to the field. These studies are supported by statistical analysis and experimental observations for healthy and stroke-affected patients. Additionally, issues and future opportunities are examined by showcasing various prototypes. The paper also briefly reviews the current market scenario for Soft Exoskeleton.**

I. Introduction

Statistics show that out of 15 million people worldwide that suffer from stroke, 5 million are permanently disabled [1][2]. Stroke patients could highly benefit from Soft Exoskeletons. Soft exoskeletons are compliant, the walking movement of the stroke patients can be restored.

Soft Exoskeleton is a field of Rehabilitation Robotics[3]. Soft Exoskeletons are advanced as wearable machine to allow movement of the limb, hand or spine with increased robustness and tolerance [3]. They are also known as Soft Robots, Soft exosuit, Wearable Robot Suit, Wearable Machine, etc. Scientists simply describe them as comfortable pants that help patients walk. These pants give power to the legs making it easier to walk. They are highly tractable and flexible since they are made up of soft material [4].

The history of exoskeletons dates back to 1960s, General Electric was the first to develop exoskeletons that was named as Hardiman. But it was heavy and only provided its application in the military [5]. Exoskeletons provide support and act as a framework for muscles. Keeping this in mind, the scientists first developed hard exoskeletons. Hard exoskeletons are very rigid, not stretchable and are very heavy and thus restricting their degree of freedom[6]. These exoskeletons had compliant actuators and rigid structure [7]. The descendant of this is the exoskeletons consisting of compliant actuators and soft structures which was complaint only to a certain extent [7]. Then came Soft Exoskeleton with improvement in compliance [7]. Thus, this innovation has been used in a wide range of applications in the health industry, especially for patients that are affected by stroke.

II. Concepts

A. Design and Fabrication

Materials: Traditionally silicone was used to make soft exoskeletons. Recent developments utilize fabrics to make soft exoskeletons. Soft exoskeletons can be made out of 3D printing techniques[10]. Such techniques are used to make sure that the soft exoskeleton is light-weight, comfortable to patients use, flexible and to maintain good aesthetic presentation. 3D printing techniques also allow us the flexibility to customize the materials. Shape Memory Alloy is one smart material that has been used to make soft exoskeleton [8]. Some other materials that can be 3D printed for making soft robotic suits are Dielectric elastomers, Shape memory polymers, hydrogels, fluid elastomers and smart soft composite [8]. The exoskeletons made out of these suits contain muscles that act as the motor nerves found in our body to help patients walk[4].

Compliance: One of the important units of the mechanical system in the exoskeleton is compliance as it allows the natural movement of the human body to be mimicked. The term compliance concerning exoskeleton is “Reciprocal of Stiffness”. Compliance works by transmitting input (force or displacement) from one point to another point through the deformation of an elastic body [9]. Compliance is needed to support the patient’s kinematics and dynamics[7]. The compliance mechanism is used because of the advantages it offers. A few of them are discussed below: It can be easily integrated with actuators. Friction is not produced and hence eliminating the need for lubrication. It can be scaled at the micro or macro level. Compliance can be achieved by using a wide range of materials. The materials used can be lighter. The entire compliant system can be made light because there are not many mechanical components (like springs, hinges, etc.) involved. Compliance also plays an important role in safety[10]. The firmness of a material is measured by Young’s modulus. The Young’s modulus of the skin and the material must be matched as closely as possible in order to avoid risking the patient’s safety[4].

Weight: Different patients have different body types; each person wears clothes according to their size. Similarly, the suit of the soft exoskeleton is better when personalized, in terms of walking and comfort to the patient [8]. Researchers at Harvard are aiming to provide personalized soft exoskeletons [8]. But it comes with an added cost [11].

Personalized design for comfort: Different patients has different body types; each person wears clothes according to their size. Similarly, the suit of the soft exoskeleton is better when personalized, in terms of walking and comfort to the patient [8]. Researchers at Harvard are aiming to provide personalized soft exoskeletons [8]. But it comes with an added cost [11].

B. Control Systems

Control: For the exoskeleton to perform its operations safely and effectively, compliance control must be implemented. Compliance can be controlled by controlling two factors-force and impedance [12]. Force control is achieved by controlling the desired interaction force and position of the robot [12]. Impedance control is based on controlling position through commands and measurements [12].

Actuation and types of Actuation: Actuators are a necessary component in any exoskeletons as they control and run the compliant parts of the exoskeleton. Actuation in earlier robots contained electric motor containing gears to work[13]. In fact, many successful exosuit use electric motors that pulls cables attached to the user's body. However, other types of actuators that can be applied to soft exoskeletons, they are:

- Shape Memory Alloys [14]
- Fluid Elastomer Actuators [14]
- Shape morphing polymers [14]
- Dielectric electro-activated polymers [14]
- Magnetic/ Electro-magnetic actuators [14]
- McKibben Actuator or Pneumatic air muscles[4].

Classification of Actuators: Actuators can be classified based on the type of motion and the type of medium. Soft exoskeletons mostly use pneumatic or electrical (cable) based which are based on the type of medium. Cable based actuators produce kinetic energy through electricity. They are responsible for producing torque. A pneumatic based actuator converts energy (energy here refers to compressed air on the piston) into motion. Pneumatic actuators can produce two range of motions: rotatory and linear. They are used in soft exoskeletons because they are safe, economical and capable of supplying high power.

Placement of Actuators: Actuators can be placed near the patient or far off from the patient [7]. Actuators that are placed offboard provide the necessary speed, power and torque[11]. Actuators can also be placed on the waist of a patient or can be carried on a backpack [7][15].

Transmission Cable: A frequently used transmission cable is the Bowden Cable because it is flexible[7].

C. Sensing

Traditional robots that use sensors cannot be applied to Soft exoskeleton. New and better sensors must be designed to adapt to soft exoskeletons. In addition to this, they must be cheap, strong and flexible.

Types of Sensors: Resistive Sensors, Piezoresistive sensors, Magnetic and Optical are the types of sensors that are used for measuring the actuation and also to perform gait analysis [16][17]. Harvard Bio design Labs have been using gyro, pressure sensor, IMU sensors [13]. The sensors are combined along with the soft elements of the system.

D. Degree of Freedom

Torque: Torque is necessary to cause an object to rotate. Soft materials are capable of imparting the desired force and torque[18].

Wearable: The exoskeleton can be fully wearable on a patient's body or it can be partially wearable. Meaning, the entire system can either be worn on the patient's body or only a part of the system can be worn. Certain parts that are heavy can be placed far off from the patient's and can be remotely used, hence making the suit lighter.

The following figure 1 shows the integration of the concepts that make up a Soft Exoskeleton.

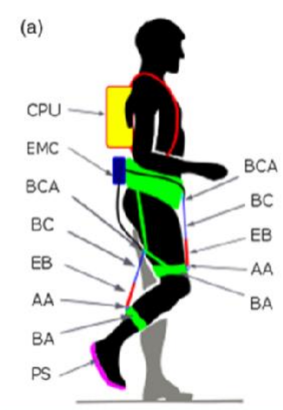


Figure 1: Conceptual drawing of XoSoft prototype with all its parts named. {"Actuator Attachment (*AA*), Body Attachment (*BA*), Bowden Cable (*BC*), Bowden Cable Attachment (*BCA*), Elastic Band (*EB*), Electromagnetic Clutch (*EMC*), Pressure Sensor (*PS*) "}[4]. Image use pending permission from the XoSoft Eu company and is sourced from one of its publication [4].

III. Experimental Vallidation

A. Outcome Variables

Walking Velocity: In stroke patients the walking velocity was recorded as 0.8 m/s during an experiment performed on a treadmill [15]. The walking speed in healthy patients was recorded to be 1.25m/s[19] to 1.5m/s[20]. The walking speed in stroke patients is good enough and can be improved with the advancement of exoskeleton [21].

Heart rate: During trails the heart rate of the participants was continuously monitored. Sensors have been placed on the suit to collect the data. Certain patients felt anxious and uncomfortable.

Balance: Some exoskeleton has sensors embedded on the suit to measure the balance of the patients. With stoke patients they needed to hold on to something while walking whereas with healthy patients the desired balance was achieved.

The figure 2 below shows the experimental setup for a patient walking on a treadmill wearing the soft exoskeleton. The below figure is shown for understanding of the experimental setup.

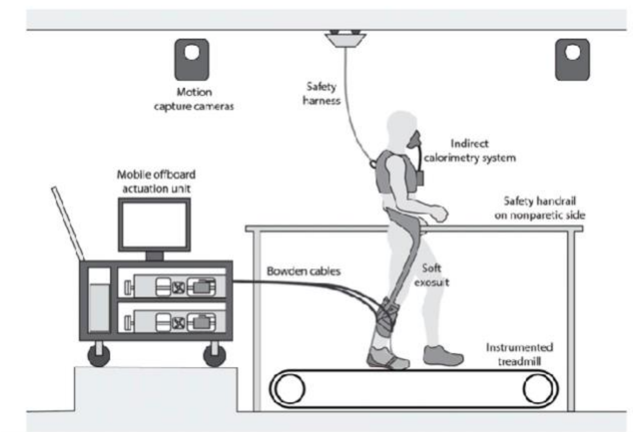


Figure 2: Experimental Setup. Image use pending permission from the Science Translation Medicine and is sourced from [15].

Evaluation of experiments: The table II (under Appendix) represents a statistical evaluation of some of the reference articles mentioned in this review paper.

B. Sample Population

A minimum of 1 to a maximum of 20 people both male and female, both healthy and stroke affected participants have been participated in clinical trials. During each of these clinical trials, patients gait velocity, heart rate, respiratory and their metabolic feedbacks was recorded [14] [24-28].

C. Task

The tasks that are performed and tested on exoskeletons are running, walking either on a treadmill or on the ground, and climbing stairs. Each of these tasks are asked to perform anywhere between 7 minutes to 30 minutes of time. These are the ways in which the patients were given gait training. Some patients required extra support while performing these tasks.

IV. Market

According to Global Market Insights, the Soft exoskeleton Market size is expected to grow to $3.9 Million by the year 2025. The geriatric population is going to benefit from the exosuit to a great extent.

A. Current Companies

Several companies are working on Soft exoskeletons for application on stroke patients. Few of them have become successful in releasing their product in the market.

- ReWalk Robotics Ltd is one of the leading manufacturers in soft robotics. Their device ‘ReStore Exosuit’ has been FDA approved and is one of the devices that has been used in improving the quality of life in stroke patients. Its specialty is that the suit is lightweight, versatile and determined by data[21].
- Ekso Bionics has about 10 years of experience in exoskeletons and has dedicated to help with medical and industrial applications. They developed Artemis which is light and adaptable. Their device only weighs 13 pounds, and this was their 30th US patented device [22].
- SRI is another company that emerged as a leader in exoskeletons. They have developed SuperFlex technology which is a “soft biofedelic actuated suit”. It has been designed to endure stress and impede damages and injuries [23].
- SuitX of US Bionics Inc has a dedicated device called as “PHOENIX Medical Exoskeleton” to help patients who cannot walk. The suit only weighs about 27lbs and has a walking speed of 0.5 m/sec [24].

V. Discussion, Current Challenges and Future Work

Although there are many challenges in building the Soft exoskeletons, the progression that it has made is excellent. Transition from wheel chaired devices to soft exoskeleton will make a significant impact on stroke-affected patients [22]. Few of the clinical trials performed on the patients indicate that soft exoskeletons are safe to use. The soft exoskeleton as compared to the hard one is light and provides a wider range of motion[23]. Some exoskeleton provides safe training whereas others have known to cause swelling and fractures in participants [24]. Forces must be applied normal to the skin in order to avoid aches and pains. It also avoids obstructions [11]. The walking speed of a stroke patient wearing soft exosuit can be improved with advancement in technology. Walking speed and balancing is greatly affected by weight of the suit and also placement of the actuators. Sitting on the wheelchairs for prolonged period of time has known to be a risk to the heart because there is no physical activity of the patients [24]. In practice the soft exoskeleton must be available to all body types, sizes and weights. Soft exoskeletons must allow stroke affected patients to live a normal life by performing all types of physical activities. It must exhibit high performance for long hours of usage. The exoskeleton and its associated devices must be friendly to the patient and must not cause any harm to the skin or to the tissues. A slight increase in pressure can cause injuries to the tissues. The exoskeleton must be safe, practical and affordable[25].

TABLE I. COST OF AVAILABLE SOFT EXOSKLETON

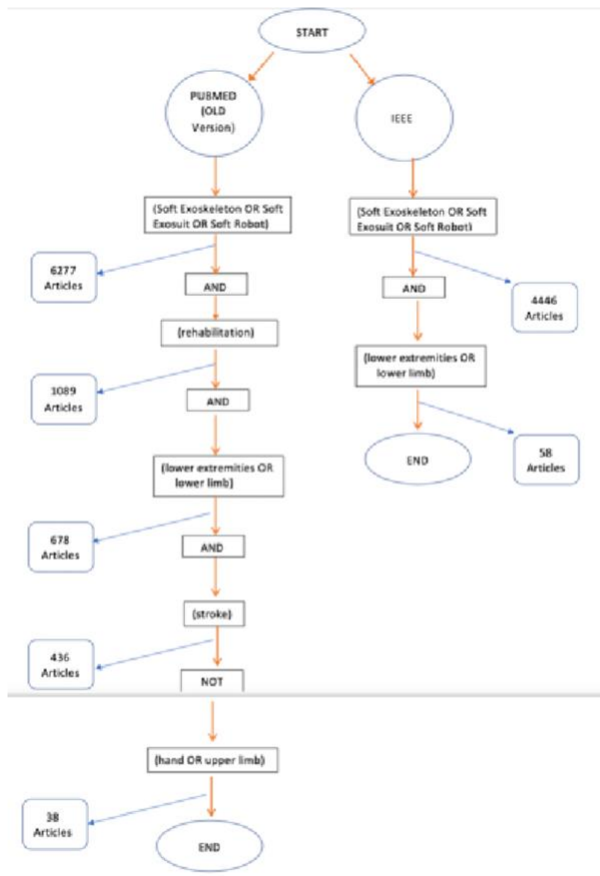
Company	Device	Weight (lbs.)	Cost in US Dollars
SuitX	Phoenix	27	$40,000
ReWalk	ReStore Exosuit	51	$69,000-$85,000
SRI	SuperFlex	7	$1,000 (Target price point per full suit)

Future work includes improving the soft exoskeletons in terms of its design and in terms of exploring other materials that are flexible. The size of the actuators should be minimized so that it can be easily carried on the soft exoskeleton[4]. The amount of rigid materials and the hardware's used to drive the exoskeleton must be reduced [4]. Soft exoskeleton must be low-priced (refer table 1) and must be able to meet the demands to those in terms of manufacturing and production by implementing 3D printing technologies[8]. Must also be able to safely react to the users. Care must be taken to avoid pressure ulcers and decrease stumbling[26]. Future activities will focus on reducing or eliminating each of the above-mentioned challenges. Harvard Bio design Research and Development team aims at providing light weight, efficient, low cost soft exoskeleton[27].

METHODS

I have applied the following search query on PubMed and IEEE :(Soft Exoskeleton OR Soft Exosuit OR Soft Robot) AND (rehabilitation) AND (lower extremities or lower limb) AND (stroke) NOT (hand or upper limb) and on IEEE: :(Soft Exoskeleton OR Soft Exosuit OR Soft Robot) AND (lower extremities or lower limb). The result was brought down to 38 articles in PubMed and 58 articles in IEEE which consisted of conference paper and journals. In total I have referred to 20 articles, mostly journals. The following flowchart (Fig 1) explains the search method that I have used on PubMed and IEEE to collect my articles of interest. The result view by each term is depicted on the left most and rightmost side of the flowchart. I have used advance search techniques to find the reference articles.

Figure 3: Flowchart Method to find articles



APPENDIX

TABLE II. STATISTICAL EVALUATION

References	"A soft robotic exosuit improved walking in patients after stroke" [15]	"Biologically inspired Soft Exosuit" [28]	"Effectively Quantifying the Performance of Lower-Limb Exoskeletons Over a Range of Walking Conditions" [29]	Influence of a Soft Robotic Suit on Metabolic Cost in Long-Distance Level and Inclined Walking" [30]
Sample Size and Sample Selection	n=7, ambulatory individuals (Paretic and Nonparetic), 9 participants were recruited for this study	N=5, healthy subject	N=8, healthy subject	N=1, Healthy male subject (age = 79 years)
Experimental/ Observational Study	Experimental	Experimental	Experimental	Experimental
Within Subjects vs Between Subjects	Within Subjects	Within Subjects	Within Subjects	Within Subjects
If between, were measures	N/A	N/A	N/A	N/A

taken to match/ normalize				
Statistical Method used	Paired two-tailed t test	1 Sample T-Test	One-way ANOVA	Paired t-tests
If parametric, was normality evaluated	Normality was evaluated	Yes, normality was evaluated	Yes. For kinematic trajectories	Yes
If linear analysis used, should the data fundamentally have a linear relationship?	Yes	Yes, with respect to displacement	Linear Analysis was used, MATLAB was used. But the linear relationship has not been shown anywhere.	Linear analysis was not used
My qualitative evaluation of the statistical methods	This research uses suitable statistical technique by collecting descriptive information about evaluating the exosuit influence on participants and offers a reasonable explanation for improvements in paretic limb function by doing an experimental study.	The study recruits 5 healthy subject to show a minimal effect on gait kinematics by applying suitable parameters in the design of the exosuit	The study uses One-way ANOVA.. The study could have showed a graph depicting the linear relationship for the performance of the exoskeleton.	The study compares the metabolic cost between two conditions, statistically significant differences were noted. Paired t-test was used.

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