Evaluation of Upper Limb Assistive Device of 1 DOF and 2 DOF Grip Motions for Stroke Patients

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Abstract

Cheap solutions for exoskeletal gloves that are powered by physical motions of body are very less in the market with many of them requiring electronic setups and programmable devices to work. The exoskeletal wearable equipment is widely developed to help/assist in human body motion. The need of such devices is much more than ever predicted owing to the day by day increase in number of patients with stroke and paralysis or the use is not even limited to patients but such devices can be used as an additional support for those who are healthy as well. Another factor regarding available devices is their weight which is very important while considering usage specially by elderly patients. Orthotics is a field in which design and development of those medical devices are carried out which act to support, aid or modify the functional and structural characteristics of neuromuscular and skeletal system of human body. Various Robotic Exo-Gloves have been tested in labs for development of assistive devices for stroke patients to make them capable of performing ADL. However mostly the systems developed are either very complex or they are not compliant and even become source of difficulty for patients. This can have adverse effects on the joints and motor function of the body and thus not feasible. This research deals with the evaluation of an upper limb assistive device for gripping motion in both 1 and 2 DOF mainly for stroke patients and also for healthy individuals with weak joints or in elderly people. The purpose of this study is to evaluate the effectiveness of a body powered and wearable Exo glove for stroke patients.

Keywords — Orthotics, ADL, Exo-Glove, Tendon driven, Rehabilitation, ATs

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1. Introduction

The hand as part of upper limbs in the structure of humans is the extraordinary constituent of the anatomy and according to body motions most adjustable and agile motor mechanism [1]. Daily life activities are mostly carried out using limbs in human body. If there is a malfunctioning due to stroke or any other reason the activities might get restricted and a patient might need help/assistance to carry out basic daily life tasks. People affected by trauma like osteoarthritis, muscular dystrophy or stroke are likely to get musculoskeletal therapy to train their muscles and for rehabilitation. Following any trauma, the therapeutic treatment should start as soon as possible to recover the body parts movements either partially or completely. The delay in treatment can cause spasticity with time in muscles. Spasticity is a condition in which normal fluid movement is restricted and disturbed due to muscles stiffness and tightening. The contractions of muscles deprive them from stretching thus having adverse effects on ADL like speech anomaly, muscle motion and gait abnormality. Today's Medical science adopts treatment like functional electrical stimulation (FES), Neurophysiological approaches, EMG-BFB (Biofeedback) and Physical Therapy for recovery of motor functions after stroke or paralysis. FES is a treatment in which small electrical currents are applied on human limbs to enhance mobility and dexterity in patients of stroke which may be a result of brain or spinal cord injury. Surveys have indicated, in Australian region along with many other areas worldwide, most of the aged people who are differently abled have been suffering from different CV diseases. In US around more than 700,000 people undergo such diseases. By the year 2050 it is even predicted that the number may rise to 1,330,000 cases a year. It is one of the leading cause of permanent disability [2]. People older than 45 are at a high risk of getting stroke as obvious from numerous researches that with an increase in age chances of stroke rise substantially [3]. A considerable proportion of research-work is being undertaken regarding stroke due to its ability to cause inadequacy in nervous system and malfunctioning in mobility of joints etc. [4]. One of the most affected function of human body in stroke is motor function which is required for survival. Patients with impaired motor functions following stroke will be showing abnormal function in case of muscle activation, coordination of muscles motion, loss of focus, error free movement and abnormal dexterous approach to ADLs. Researchers associated with the field of Robotics are always fascinated by the function of human hand and its motor functions. They always try to mimic the function of human hand in basic robotic motor functions and complex motions. A major concern of rehabilitative studies have always been to understand and repair hand motor functions after a person has had a stroke, since the human hand plays a vital role in the daily activities of a person's life [3]. The research in [5] shows that most of the positions of gripping motions corelate to almost 75% grasping arrangements required for performing ADLs. Grasp types included in the experimental batch are Cylindrical (Bottle, Hammer, Coffee Mug etc.), Hook (Plastic case, Tool box etc.), Lateral (Compact disk, ID card etc.), Palmar (Small items, Match box, PVC Tape roller etc.), Spherical (Tennis ball, Oval Perfume bottle etc.), Tip (Pencil, Eraser, Screw etc.). Most of these tasks can be performed by using Thumb, Index and Middle fingers that are very vital for grasping, while the other 2 fingers have subsidiary role in assistance [6]. Such consequences are the basis on which the design of simplified robotic assistive devices is laid that offers lightweight, cost-effective and result oriented end product instead of trading off on their comprehensive capability [7]. Many researches are committed to studying different forces exerted by human hand as a healthy subject which shows that a human hand is able to produce maximal grasping torques which might stay between 67.5 lbf to 101 lbf [8]. considering several publications researchers carried out experimentations for calculating the force exertion capability of body's end effector (upper limb) along with fingers and they found out that the necessary forces required to carry out routine tasks of ADL do not go beyond 10-15 N. since last 10 years, the sector concerning orthotics or Exo-Gloves is rising many folds in terms of research and clinic involvement. Many assistive devices and Exo-Gloves have been developed to assist the human limb movement and improve dexterity and enable them to easily perform ADLs [9]. The assistive devices like Exo-Gloves are possible to be powered with different techniques like actuators, tendon wires, mechanical pulley like structures etc. Moreover, while considering recovery of human hand motions, foremost thing to look up is the process which can be utilized to optimize the functionality. One of the major conditions of those who survive is immobility of hand or upper limbs. Exoskeletal robotics have emerged recently in modern neuromuscular rehabilitative engineering and development of assistive devices for individuals with the need. The tremendous work being done on the development of this sector shoes promising outcomes in the improvement of upper limb functionalities vital for carrying out numerous tasks in ADL.

The possible reason of immobility of hand in case of paralysis is disturbed Cerebrospinal fluids, mainly due to internal bleeding or restricted blood flow in body, following Malfunctioned and abnormal signals of nervous systems. Impairments vary according to the indication of disturbance in certain areas of system. Cerebral, psychological and neurological chaos may arise following initial attack, nonetheless hand and arm malfunctioning or hemiplegia mark as frequent kind of disability [10]. Regarding upper extremity barely around an average of 12% people recoup proper capability to carry out routine tasks after 180 days of the disease, and around 40 out of 100 will recover in terms of paraplegic upper extremity [11]. Recovering hand motor functions in patients is one of the main focus of Assistive Technology field. Around more than 35 % of the Assistive technology in Therapies are focused to improve the condition for performing activities of routine [12]. Many research publications show that a focus on physical and psychological improvement with direct involvement of the patient is very important for the stimulation of hand mobility after the disease [13], [14]. Weakness and disability of hand and arm in such patients give rise to serious complications while performing hygiene and other tasks of ADL particularly when these tasks are related to gripping the items in hand. Such issue causes limitations in patients while performing their tasks independently along with reducing the standard of living. [15], [16]. Following a year after suffering from stroke, a large proportion of patients need therapy for performing their tasks of life [13].

Technological oriented uplift, in the development of upper limb Orthotic devices known as assistive technological devices, has provided with the new avenues for compensation of motor function losses by giving the required support to the upper extremities specifically forearms while performing tasks of routine [15], [17]. The definition used for Assistive technology in this evaluation study is related to proposition by [18] and [19]. Upper limb Orthotic Assistive mechanical devices can be referred to as "The devices which are formulated and designed to help patients with motor limitations by providing direct aid and support to the motion of upper limbs." Assistive Technologies (Exo-Gloves) shows huge potential to help out in augmentation and support for utilizing upper limbs specially hands are vital for gripping motions. One of the great benefits of such devices is that they do not require prolonged clinical appointments and also easy to train patients in the comfort of their homes. These devices also help in physical therapy of muscles so as to train them and avoid muscle weakness thereby. Another great feature of such devices is that they can be used by patients in increasing their motivational activities whether it be any physical activity or exercise in form of gaming etc. that they love to perform. In this way patients can avoid boring monotonous routines and can attain the feeling of being independent. ATs are excessively used to escalate traditional physiotherapeutic activities and occupational therapy. In spite of indecisive practical endorsement of Exo-Glove technology, many research studies are underway for their development and best possible solutions. Hence there is an essential requirement that the development should be done based on pure practical basis to check the usefulness of the devices and also keeping in mind aesthetics for the end User. Developing medically beneficial Exo-Glove Assistive devices require deliberation of numerous aspects including many other challenging elements such as efficacy, expenses, utility and aesthetical sense hence demands apprehension based on patient's prime concern. Study shows conjecture regarding causes of transformation of Exo-Glove technology to routine medical procedures yet meagre factual findings of the matter. Mostly Assistive devices for upper limbs require a soft glove to be used for gripping motions. Thumb, Index and Middle fingers are vital for gripping objects by human hand. Extension and flexion of these three fingers are necessary to achieve the gripping motion in flexion position of three fingers at the least.

Figure 1-1: A soft glove used for forced Flexion and Extension of three fingers required for object gripping.

In [20] author proposes a portable high performance hand exoskeleton (HE) that is able to exert forces in a range of only few Newton's (5N) with the help of a transmission system that still needs improvement for being more efficient mechanically. In [7] author proposes a tendon driven exoskeletal glove made of silicone which can help a patient to hold around 1 to 1.5 kg weighing items. It is actuated with the help of a battery and it weighs more than 1.5 kg and can apply up to 40 N gripping force. In [21] researchers have proposed a force transmission system using wires. Assistive device which is possible to be actuated by different control strategies and produces gripping power of around 3.3 lbf with the help of servos connected with tendon wires. In [22] author proposes a soft extra muscle glove which is a tendon driven assistive device which is able to produce roughly 0.8 lbf but its cost is so high. In [23] author proposes a soft Exo-Glove that can provide around 8 N of tip forces with the help of a hydraulic system. In [24] author proposes a soft robotic Exo-Glove that utilizes a pneumatic system to actuate and can apply around 9 N of force at the tip. Even though the above-mentioned designs on Exo-Gloves can provide a considerable enhancement in the standard of life of stroke patients with physical and motor disorders yet they have various restraints. First of all, these devices need an external power source to be operated and as a result their independence is restraint. Moreover, when these devices become costly when different actuation systems are utilized for their function like pneumatic system, hydraulic actuators, servo motors and advanced sensors. In addition to all these issues another main concern is their weight which should be in a specific limit to let the patient carry the assistive device with great ease and comfort. Another important factor to be considered while designing an assistive device is that the patient becomes dependent on power source because most of the devices are battery operated so this feature limits the time for which an assistive device can work after which it needs either a recharge or battery replacement. Therefore, an assistive device independent of power source, easy to operate, cost effective, reduced weight with operating time unlimited is crucial for stroke patients or human assistance in ADL. Such a device is possible only if it's purely mechanical and is powered with the help of healthy muscles in the body of the patients. These devices can be used to rectify and prevent deformation and rigidity of the affected limbs in stroke patients [25]. The time period for which the device should be used depends on severity of the affected part of the body and on current condition of muscle dystrophy primarily [26]. Assistive devices can be utilized for some specific motions as well by keeping in mind certain limitations for particular areas/parts of the body e.g., hands. Using mechanical forces from healthy parts of the body to actuate the mechanical device as a transmission system to mobilize the effected part of the body. For movement of the hand, forces can be generated by alternate healthy shoulder muscles.

In Figure 1-1 we can see a soft glove that is being utilized to aid the patient in grasping objects. The motion could have been achieved by using a ratchet mechanism with tension wires which remain intact with the fingers. Tension forces applied on the wires help to produce flexion movement in the fingers. Patients suffering from stroke are unable to move their fingers with brain commands and they need training of upper limbs to restore the motion which is possible by using such techniques and mechanisms. The differential devices used for extension of wires can be either pure mechanical or motorized. Motorized devices available in the market are either very expensive or they have heavy weight and the patients are therefore unable to withstand the load of such devices, creating an extra burden on already dependent person/patient. Mechanical assistive devices can be powered by using muscle motion of the body. The parts which are healthy can be used to produce extension in the tension wires which in return apply force on glove and thereby bending the hand in flexion motion. The human hand is a very complex structure. It has more than 20 DOF which makes it more adaptable and dexterous part of the body [27]. The composition of hand consists of bones, muscles, tendons, neurons etc. and the motion of each joint is very complex which helps a normal human being achieve daily life simple tasks but with complex joint motions if observed closely. Finger mobility restoration is the basic need for rehabilitation of hand functions which is the end effector of the upper limb and is mostly used for carrying out ADLs. Most of the devices available for upper limb restoration are heavy, costly and complex in nature.

The purpose behind this study was to evaluate an upper limb assistive device that is powered by body and driven by using tendon wires. The research will focus on the evaluation of the design of Exoskeletal assistive device and its effectiveness in restoring the lost mobility of the patient's hand. The device that is evaluated in this study consist of Exo-Glove and a differential transmission mechanism that gets its input of force from a healthy muscle and divides the force between three tendon wires and transmits them to index finger, middle finger and thumb. The main purpose behind this study is to evaluate and analyze the performance of this device and how applicable the device proposed in [1] (Body powered Exo-Glove) is for practical application in supporting the patient in performing ADL.

2. Design and Components

I. Evaluative Requirements for Assistive Devices

This segment narrates the considerably crucial conditions for the accessories meant to be used for upper limb aid in tasks of ADL. As a consequence of the obtainable publications and deliberation with rehabilitative specialists and physicians, the main essential demand for upper limb assistive technology devices can be listed as follows [28].

i. Reciprocity of the Movement

The arrangement of the device should assist the motion in both directions, i.e., opening and closing of finger (flexion/extension) and to function more accurately the finger movement should mimic as close to human hand motion as possible. Independent movement of fingers if possible is a greater advantage in human hand motions.

ii. Usability on Hand

Usability is generally defined as the measure of the scenarios for its end users to carry out the ADL in safe, effective and efficient way possible. The assistive device should be easy to wear on hand (which suggests complete mobility of the product) so that the patient can be able to roam freely while wearing the device.

iii. High Power-to-Weight Ratio

The device should be light-weight and compact and is efficient to produce enough output impact and velocity, which suggests an Exo-Glove with high power-to-weight ratio.

iv. Free Wrist and Palm

While using the device for grasping the objects, it should not put any limitations on the movement of the other joints of the arm, such as wrist and elbow joints. It should only independently affect the flexion and extension of the fingers required for grasping the objects.

v. Safety and Comfort

The assistive glove should be really secure and comfortable for the user and it should not become source of unease for the already disabled and challenged patient. The device should support the wearer in a way that it doesn't cause any damage to the part where it is worn. For systems with an active control mechanism safety is the foremost requirement and it should be fulfilled and properly tested for all safety measures before handing over to the end user. If the forces don't transmit in a way, they are intended to then it could possibly cause damage to the interacting body part (hand in our case). Therefore, the interaction between the device and hand is very crucial. The mechanical actuation in motor-controlled systems and manual devices should make sure that the spontaneous and natural movements of the hand are supported and should not instigate peripheral injury to the patients, particularly for the assistive devices. Mechanical termination of the device, forces restrictions or restricted rotatory motions can be utilized for designing such devices to avoid ROM movements beyond the natural constraints of the hand motions. Such design features and properties are being implemented in [29], [30], [31], [32] and [33]. The interaction of Exo-Glove with the body is the vital feature to be considered in providing comfortable assistance experience. Velcro straps should be utilized to keep the cables and tendons in place and to avoid any kind of injury.

vi. Affordability

Assistive devices and Exo-Gloves available in the market are mostly expensive and therefore out of reach of needy people. The reason is that the material in the market is expensive and the technology is relatively new and in research phase which requires a lot of resources. With the advancement in technology the assistive technology is becoming easy to afford but it will take a lot of time to get to a point where each and every person can afford the assistive devices. Instead of conventional manufacturing technologies rapid prototyping with 3D printers could drop down the expenses. Simulations can be made to ensure the optimization of material cost and also efficiency of the devices. The quest for the ultimate best design for the accommodation of all necessary conditions is still under consideration. The assistive devices must be under certain limit of expense to enable every needy person to purchase it easily and also, they should be in such a great number that could allow medical rehabilitation community to accommodate for their patients. Those assistive devices which are customized for users are relatively expensive as compared to a generalized device that could be used by any patient with any hand dimensions. Low maintenance requirement and usability is also a necessary condition to be achieved in the design of Assistive Exo-Glove.

vii. Adaptability

The assistive devices made should be generalized for each and every person. Every person with varying hand dimensions and multiple problems should be able to sue the device and that too with ease and confidence. This condition is necessary because there are different patients who will need the device for either rehabilitation or for assistance to healthy individual as well. Each and every patient can have different dimensions of hands that’s why this condition becomes vital if a generalized device is to be considered. The assistive device evaluated in this research has been developed for use by various patients having multiple hand dimensions. This is foremost and important condition that needs to be fulfilled by an assistive device that is being generalized for use by different hand dimensions. The main mechanical device (differential) proposed by [1] makes it standout because of the fact that this device can be adjusted for different hand dimensions. Sandoval-Gonzalez et al undertook a research in which an average size for human hand was estimated for both genders combined within the age group of 16 above and below 70 years of age which is usable for design study of assistive Exo-Gloves [34]. This research can make a good measure of necessary conditions that are need to be met for a perfect design. Figure below shows the types of design for Exo-Gloves found in literature.

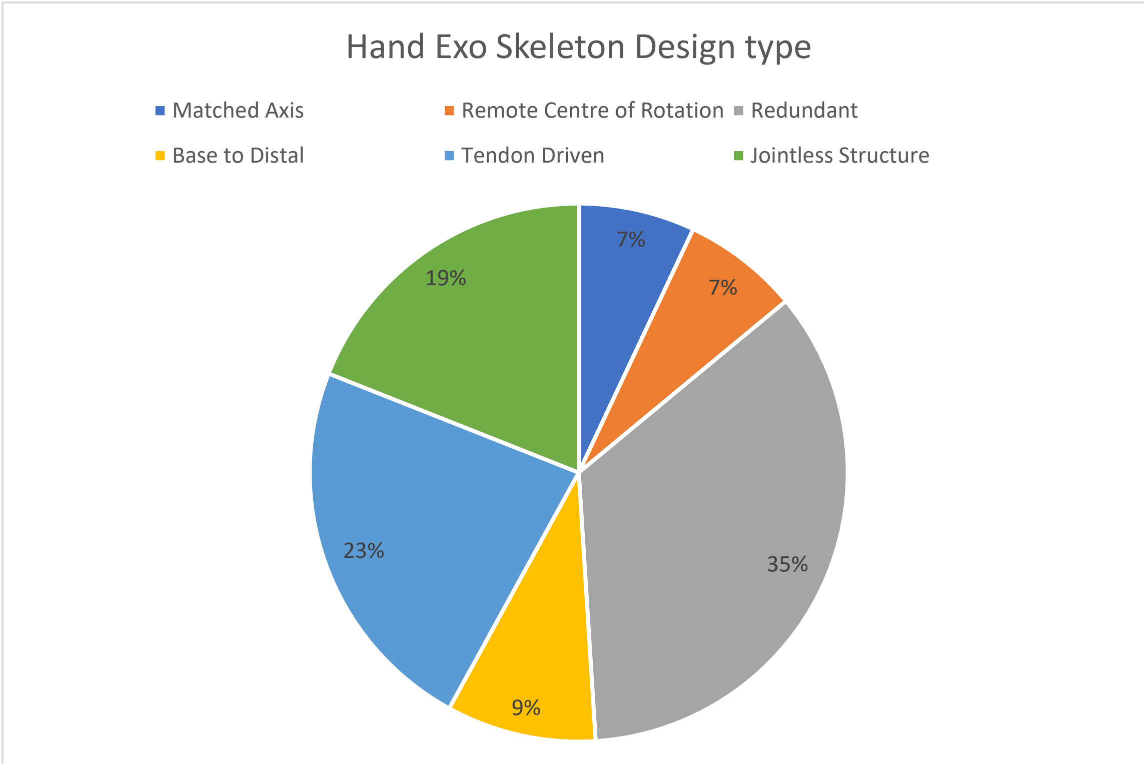


Chart 1: Hand Exoskeleton Design Types in Literature.

II. Specific requirements

The main demand of Exo-Gloves and Hand Exoskeletons are for the purpose of rehabilitation and as an assistive technology.

i. Rehabilitation

The exoskeletons are designed to help the patient for their rehabilitation as well for different disabilities and sensory motor dysfunctions. These devices can reduce frequent visits to physiotherapists for regular training. Assistive devices can be used repeatedly for the purpose of rehabilitation and recovery along with repetitive motions of hand. For hand rehabilitation they can be used to produce flexion motion and extension motion of fingers to copy the movements of fingers in ADL. To carry out constant passive motions (CPM) for individuals after the surgical procedure which will not only avoid joint spasticity but also proved to be useful in preventing rigidity of tendon muscles inside hand which will otherwise have a very adverse effect on hand motions.

ii. Assistive

Exo-Gloves are vital for being used as Assistive devices to improve the lost dexterity stroke. Patients need assistance to perform tasks of ADL and for this purpose the importance of these devices come into place because they can be used without getting extensive trainings and without visiting clinics and can be used easily and effectively without the assistance of any other person. The exoskeleton evaluated in this research is lightweight, easy usable on body, movable and autonomous. Simple muscle movements

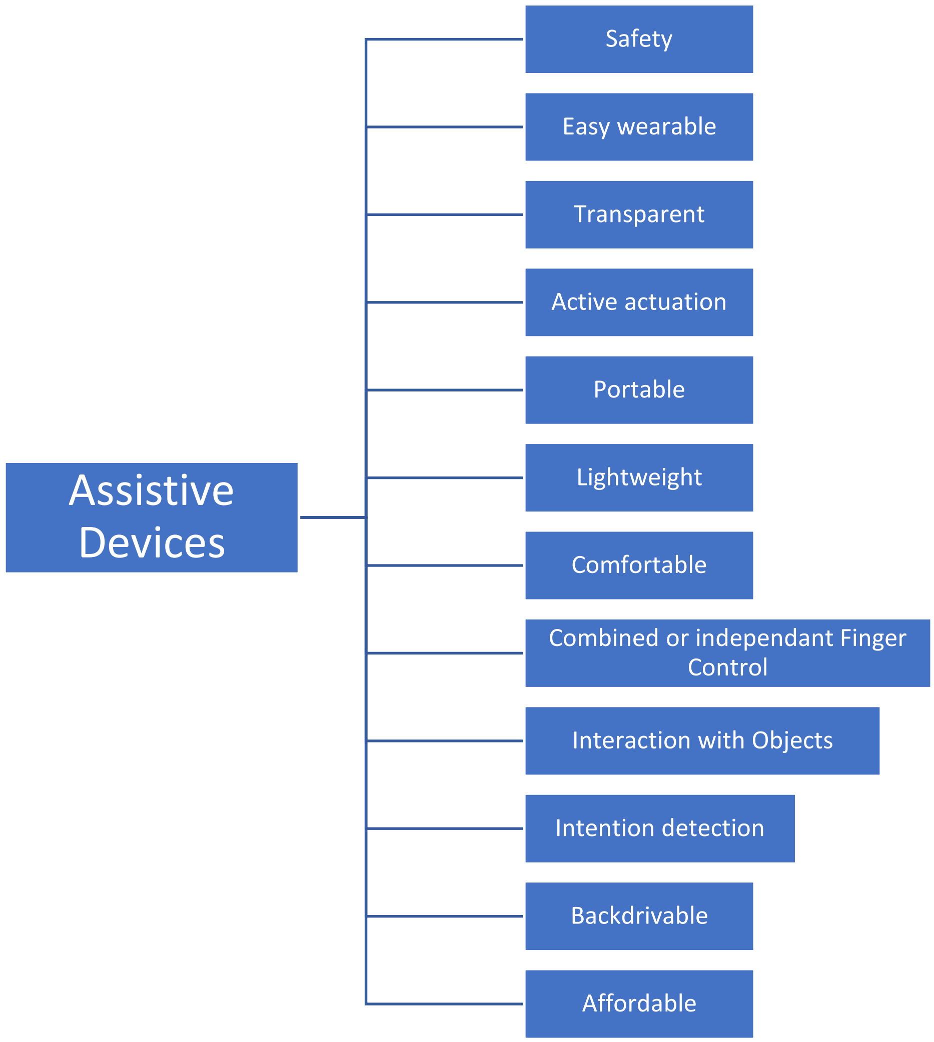


Figure 2-1: Identified General important factor required for development of Assistive Devices.

can be utilized to carry out force transmission which can help in actuating the mechanical device which in turn applies force on three fingers for creating a bending movement (Grasp movement).

III. Proposed Assistive Device for Evaluation

The assistive device proposed in [1] consists of 5 major components: a shoulder wearable harness, tendon tensioner that maintains tension in the tendon wires, a differential mechanism that divides the forces in tendons, Exoskeletal Gloves, Velcro straps for keeping wires in place, tendon routing tubes and a main tendon.

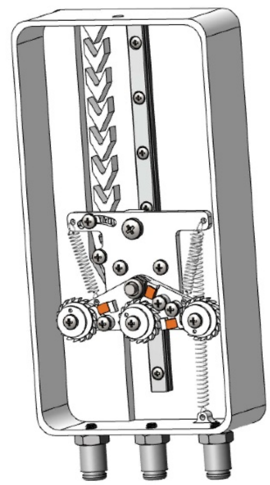


Figure 2-2: A differential mechanical assistive device used for transmission of forces from shoulder muscles through tendon wires to three fingers.
Courtesy: GEREZ et al.

The body powered wearable Exo-Glove consists of a differential mechanism that transmits the forces from one point to the other and in this research, it is evident that this device can be utilized to transmit forces to three fingers required for grasping objects. The device works as an autonomous gadget without requiring any power source and can be used as and when required easily. The device requires low maintenance and is cheap. The Exo-Glove can be used independently without the requirement of any motor and power transmission. Hand motions like extension and flexion of three dominant fingers can be easily achieved with the help of this mechanism. The differential mechanism helps in tensioning of the tendon wires and can assist in maintaining specific position of the hand while grasping any object. It evenly distributes the forces among the fingers for grasping the objects by taking in to account the under-actuation principle. The under actuated mechanical systems are defined as those systems whose controlling inputs (Motor Joints) are less than the DOF that the system can work in [35]. The under actuated mechanism can help in grasping objects and items with an irregular shape. An example of under actuated system is the differential used cars that transmits the engine's torque to the wheels. The differential transfers the engine power to the wheels so that wheels can move at different speeds specifically while taking a turn. The differential mechanism not only help in the tensioning of the tendon wires but also helps in transferring forces in under actuated scenario e.g., while trying to hold egg or any irregular shaped item etc. The under actuated differential mechanism can be used in different prosthetics and orthotic systems. The assistive device in this study uses a whiffletree mechanism which helps in adaptive grasping of the objects under consideration. The whiffletree is a mechanism used for distribution of equal forces through linkages and connections. In this case we are dealing with three fingers. Equal distribution of forces to each finger is necessary for carrying out effective grasping. It is also named as double tree. The force transmission is carried out with the help of a pivot in the center that further distributes it to tips and transmits it to more linkages as required. They can be connected in series to further distribute the force. In series whiffletree is utilized in car windshield vipers to distribute the point force from the main arm equally along the viper to have uniform cleaning of the windshield, so the above-mentioned mechanism is vital for distribution of forces in Exo-Glove mechanisms without which the grasp could not have been attained at a uniform level. These mechanisms are widely used in robotic limbs that are under actuated [36],[37]. Figure 2-2 shows the assembly of the differential mechanism that can be considered as a transmission device for mobilizing the tendons connected with each finger. The mechanism consists of the three main parts: the circular ratchet mechanism, linearly drawn ratchet and a whiffletree differential mechanism. The circular ratchet mechanism is solely of adjustment of tendons as per user demand with different hand dimensions or tensioning requirement.

Figure 2-3 (A body powered assistive device proposed by [1]) shows the circular ratchet mechanism which shows the basics of their use. Total 3 circular ratchets are used for adjustment of three tendons of each finger separately. It can lock the mechanism in certain required position which can be adjusted as per demand and need of a particular person/patient. The pawl of the ratchet prevents the motion of gear in one direction and allows it in the opposite direction. In this way length of the tendons can be adjusted

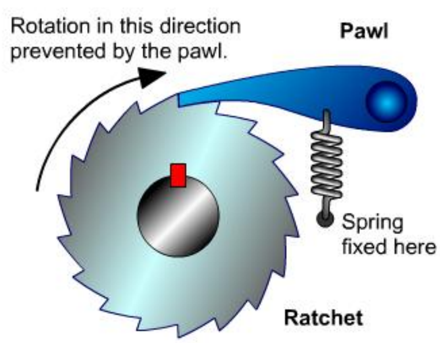


Figure 2-3: The ratchet mechanism used for tendon tensioning and adjustment

which is very crucial for patients every patient might require different adjustment for the length and tightness. This particular mechanism allows very smooth and accurate adjustment of the wire lengths and is very easy to alter. The mechanism enables a user to adjust the lengths of each tendon wire to be adjusted as per demand and need. The tendon wires pass through tubes and reach each finger on Exo-Glove. The main body has a linear ratchet as well, when a user pulls the muscle of shoulder the main tendon applies force on the whiffletree mechanism and pulls it above. The mechanism moves along a linear ratchet and locks in place when a user relaxes the muscle. In this locking position the fingers remain intact in same position for as long as the user wants to hold an item. The linear ratchet consists of V shaped teeth arranged in line with a sprung locking mechanism. the whiffletree mechanism moves on a sliding rail that is screwed to the main body. The base holds the whiffletree mechanism with 2 springs, one on each side, while the base can slide on rail up and down. When the main tendon wire is pulled by the help of shoulder muscle stretch the locking lever mechanism starts passing through the teeth and gets stuck where the user stops it. It remains in locking position for as long as the user does not pull shoulder muscle once again. As the locking lever is spring loaded it's aligned towards left of the linear ratchet. When user pulls the main tendon once again and relax it while trying to engage the system, the lever moves up and leaves the V shaped linear ratchet mechanism and starts moving downwards and comes back to the point where it started. When main tendon is pulled again the whole process starts again and it can be repeated for as many times as user needs without any power source and only stretching force given by shoulder pull. The shoulder pull works as a power source to actuate the mechanism manually. The mechanism allows the tendons to be kept in place for desired amount of time which is very beneficial feature of this mechanism. It allows the system to work perfectly while it being under actuated. In motor-controlled mechanisms each tendon is adjusted with the help of a motor which requires power source to operate. The Exo-Glove powered by healthy muscles allows the possibility of transferring forces from one part of the body to the proximal, middle and distal phalanx of the hand, with the help of tendon wires which pass inside the soft tubes, for creating bending motion required primarily for gripping the objects. So, in this

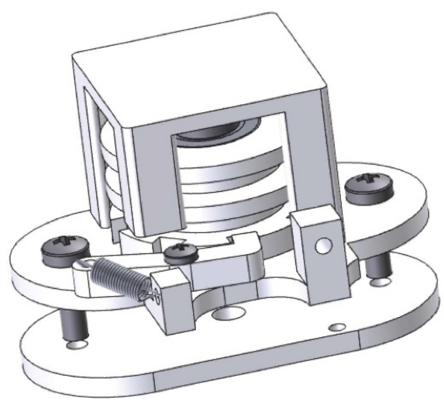


Figure 2-4: Tendons tightening mechanism used to produce tension in main wire.

case a little force applied by muscles movement can transmit considerable amount of tension in the wires and enable them to apply force in fingers. The tension in wires is adjusted with the help of tension adjustment mechanism which is crucial for its operation and working otherwise the amount of force applied will not be considerable to make an effect. Figure 2-4 shows the tension adjustment mechanism that is used to tighten the main tendon wire that connects the shoulder muscle to the differential body. This mechanism consists of a base part where all other components get connected. There are two plates in between which there is a pulley, the base of this pulley is made or rectangular teeth pattern in which a lever can lock or unlock itself with the help of a button that pushes the spring loaded on it.

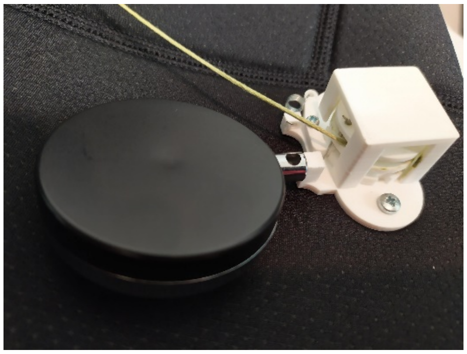


Figure 2-5: Tension adjustment mechanism along with retractable reel. courtesy: GEREZ et al

Figure 2-6: Harness for shoulders courtesy: GEREZ et al

The pulley is wrapped with a retractable reel that can recoil itself once the lever is released from the teeth pattern. In this way the proper tensioning of the main tendon is achieved. After the lever is released, the pulley rotated in anticlockwise direction and a part of the main tendon wire also gets wrapped on the pulley which pulls the main tendon wire tightly. The tensioner mechanism is enclosed in a circular shaped casing that protects the wire from external particles and also ensures that the retractable wire does not get loose and slips put of mechanism.

The tension adjustment mechanism is fixed on a harness that is worn on shoulders tightly. It also keeps the devices in place and prevent mechanisms to slip away.

Figure 2-6 shows the harness that is worn on shoulders with tension adjuster fixed on it and the main differential also fixed on the other side. Harness is kept in place because of its adjustment according to size of chest so there is no chance of slippage. Also, this fabric is user friendly and can be worn very easily. When the shoulder muscle is moved while bending forward a little the force is applied on the main tendon wire and is transferred to the differential mechanism which further divides the forces in finger tendon wires. Mainly the forces are transmitted with these wires and therefore they need to be of low friction and that's why these tendon wires are made up of a fiber which is very low in friction and highly efficient in transmitting the forces between multiple points. The fiber used is of high-quality UHMWPE due to its ability to withstand stress. The polymer has a higher toughness over weight value, less dense as compared to other fibers, negligible frictional forces, good flexibility and chemical stability. High strength Polyethylene braids are used to accomplish tough properties for demanding applications such as actuator cables in our case and anchoring devices in many other areas. The tendon starts from tension adjuster and ends at the differential mechanism. The other part starts from differential mechanism till the fingertip where they are connected to a structure made up of stainless steel. The actuation of body powered mechanism lags in time because a muscle pull force is required to achieve the task but the working of device is very simple and effective in way that it can be executed without needing any power source. The

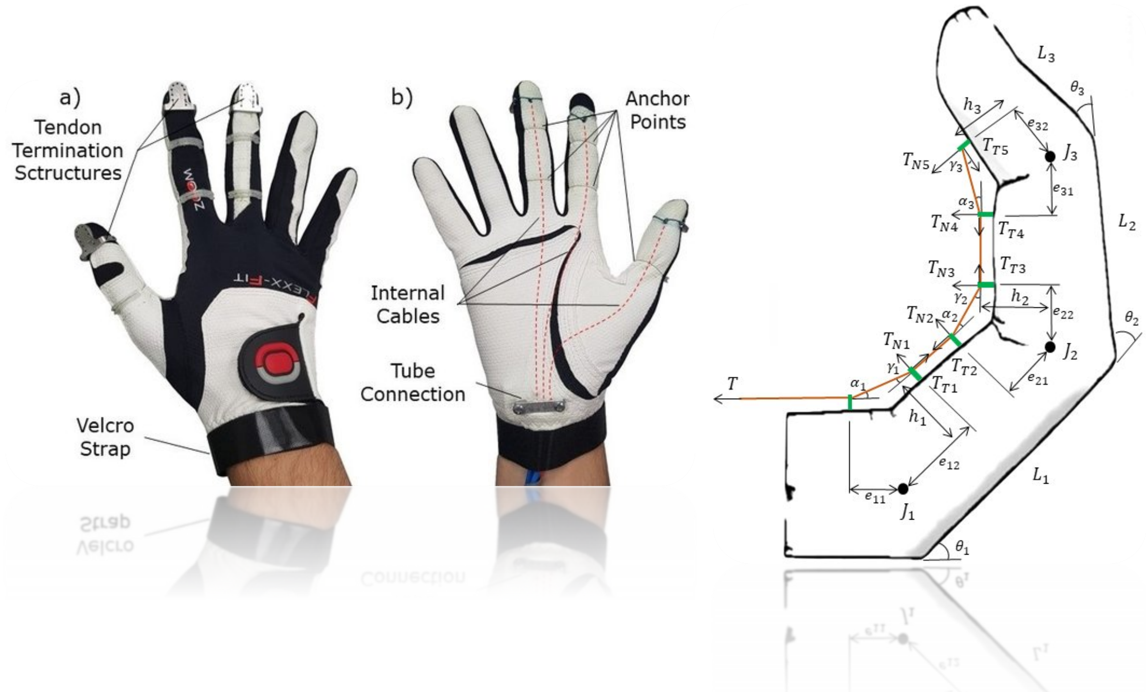


Figure 2-7: Figure shows the soft tendon routing on palm of hand as proposed by the research group. Second picture shows tension forces acting on a single finger with this tendon tensioning. Courtesy: GEREZ et al.

assistive device does not require aggressive training of the users as well and is very user-friendly. With the help of three circular pulleys the device can be adjusted for different sizes and

body types. The only alteration required in this arrangement is for glove as the size of hand will differ and harness because shoulder size will be different for different users. The upper limb assistive device weighs around 330 grams and is one of the lightest known assistive devices under research till now.

This feature makes this device stand out in terms of easy usage. The size of this device can be further reduced by making a compact system with highly efficient materials. The more compact the device will be, the more cost will be reduced and reachable to every needy person. As this is the body powered mechanism the actuator can be changed and power source can be utilized for tensioning the tendon wires with the help of motor and pulley combination. It will be beneficial for those users whose muscles are not that strong to exert the considerable force on tendon wires.

In Figure 2-7 soft glove proposed for the assistive device is shown. The reason of using soft Exo-Glove is that the soft robotic gloves are formed from the material that gets adjusted to the environment and can easily achieve shape deformation and conformation with the surroundings such as gels and soft organic materials like PU (Polyurethane), Latex etc. due to their quality of being conformable with the surroundings they have better caliber to mimic the biochemical processes due to their increased agreement and adaptability to the shape of the human limbs. The absence of inflexible parts removes restrictions on DOF and also reduces joint alliance problem which prevents the damage to the joints [38]. Additionally, the soft Exo-Gloves are light in weight and have uncomplicated design making them more probable to be handy and also to be deployed for domestic rehabilitation. This feature allows the patients to train themselves in the solace of their residence. The fabric of the proposed glove is very light weight and sensitive. Anchoring structures are used for three different fingers. Different anchor points are attached on gloves' fingers. Artificial tendons are used along with single wire prop. Suggested arrangement is made for increasing tangible responsiveness, agility along with gripping strength. Proposed surface of the glove is kept rubbery to enhance the frictional forces between glove and the object to be grasped. Tendons are placed inside the glove to avoid irritation to the end user from wires. Cables placed above the gloves can also cause hindrance in smooth contact of glove's internal surface with the grasping object and it can result in the destruction of wire structure as well which is not at all bearable for a user. At the tip of each finger a stainless-steel hook was attached with the help of high-quality stitching as shown in Figure 2-7. The main purpose of utilizing only three fingers is based on the fact that most of the task of ADL are carried out using these three fingers [39]. The final design of the soft Exo-Glove along with all the transmission mechanism inside it weighs less than 55 grams, which is very suitable for usage and is way less than the weight of the glove mentioned in [9]. For tendon arrangement along the glove PU tubes of 3mm diameter were used. A structure made of aluminium was used to screw these tubes on Exo-Glove. Everything attached on glove is properly fixed so that there is no hindrance in the movement of the hand while achieving the grip motion. The section of the tubes passing through the wrist is held in place by Velcro straps. The above arrangement prevents the Exo-Glove from fabric deformation when tendon is in motion (the issue was found in few previous studies [40]). The main distinguishing feature between Exo-Glove of above assistive device and those found in other literatures ([7], [21], [41]) is that the anchors are used along the fingers at certain points to keep the tendons in place and work effectively and efficiently without causing any damage. If the anchor points are rigid, they will hinder the object to be grasped easily and the contact region area will be reduced while in soft and braided anchor points the area of contact increases along with decrease in epicritic sensibility. These features make the assistive glove lightweight and easy to be worn. At the backside of the Exo-Glove a 3D printed spherical part is stitched to the glove to avoid injury to the hand while forces are being applied through the braided tendon fibers. Figure 2-6 shows the application of forces and detailed description of joints and anchor points. Joints are represented by J_1, J_2 and J_3. The lengths of phalanges are shown by L_1, L_2 and L_3. e shows measurement of nearest joint of hand and the plane splitting the hand in two halves and perpendicular to placed anchor. h represents perpendicular subtended displacement between anchor and plane parallel to the phalange. θ shows the angular displacement between the two corresponding phalanges. α and γ are the two angles between the tendon wires and the plane parallel to phalange. If force applied will be T then the distribution of force will be in two components T_N and T_T. T_N shows the normal force that acts on the anchor perpendicular to the plane of phalange, whereas T_T is the force that acts tangentially along the plane parallel to hand. The rotation of the finger phalanges will be effective when the torque generated is maximum, the forces acting on the anchors matter the most. They must be arranged in such organized way that the maximum torsional force can be generated. The summation of all the torques should be maximum.

(The Equations proposed by GEREZ et al. are shown below for understanding the force distribution and are put in quotation marks for proper reference. They are just written here to understand the force distribution in Exo-Glove and author does not claim to have developed them.)

“

$$\sum_{n=1}^{2} \tau_n = \tau_1 + \tau_2 + \tau_3 \tag{2.1}$$

$$\tau_1 = T_{N1}e_{12} + T_{N2}(L_1 - e_{21}) + T_{T2}h_1 - T_{T1}h_1 \tag{2.2}$$

$$\tau_2 = T_{N3}e_{22} + T_{N4}(L_2 - e_{31}) + T_{T4}h_2 - T_{T3}h_2 \tag{2.3}$$

$$\tau_3 = T_{N5}e_{32} + T_{T5}h_3 \tag{2.4}$$

The equations written above are in terms of components of forces, we can write these in terms of trigonometric identities of the forces.

$$\tau_1 = T[\sin(\gamma_1)e_{12} + \sin(\alpha_2)(L_1 - e_{21}) + \cos(\gamma_1)h_1 - \cos(\alpha_2)h_1] \tag{2.5}$$

$$\tau_2 = T[\sin(\gamma_2)e_{22} + \sin(\alpha_3)(L_2 - e_{31}) + \cos(\gamma_2)h_2 - \cos(\alpha_3)h_2] \tag{2.6}$$

$$\tau_3 = T[\sin(\gamma_3)e_{32} + \cos(\gamma_3)h_3] \tag{2.7}$$

We can find the angles α and γ by using trigonometric identities of $\sin\alpha$ & $\sin\gamma$

$$\alpha_n = \sin^{-1}\frac{e_{n1}\sin(180-\theta_n)}{\sqrt{{e_{n2}}^2 + {e_{n1}}^2 - 2e_{n2}e_{n1}\cos(180-\theta_n)}} \tag{2.8}$$

$$\gamma_n = \sin^{-1}\frac{e_{n2}\sin(180-\theta_n)}{\sqrt{{e_{n2}}^2 + {e_{n1}}^2 - 2e_{n2}e_{n1}\cos(180-\theta_n)}} \tag{2.9}$$

“

(The equations above are proposed by the research group GEREZ et al. in [1])

Equation *(2.8)* and *(2.9)* show the value of angles α and γ for all phalanges between tendon wires and plane parallel to phalange. We can substitute these two equations in to equations *(2.5)*, *(2.6)* and *(2.7)* to obtain the values of the 3 Torques in 3 fingers at 3 different joints. When the values of e_{12}, e_{22} and e_{32} are maximum that is the first anchor on a phalange is placed at the farthest distance from the previous joint and the values of e_{21} and e_{31} are minimum that is the second anchor placed on the phalange is nearest to the second joint then the value of τ obtained is maximum. Considering this condition for maximum value of the torque the anchors are placed as shown in Figure 2-6. e_{12} should be as large as possible and e_{21} as small as possible so an anchor is attached nearest to J_2 that is first joint of second phalange. Similarly, e_{31} is placed closed to the joint J_3. h in this case shows thickness of finger and larger the value of h the larger will be torque value. That means the tendon wire placed as far away from finger halving plane as possible will be better to achieve the larger value of torque.

3. Results and Performance Evaluation

The experiments conducted to check the performance of this device shows promising results. Gripping tests were performed using different objects and getting them grasped by body powered Exo-Glove and checking the feasibility of the operation. The evaluation is based on the performance of the Exo-Glove to grasp the object with a nice gripping force.

Table 3-1

Parameter	**Strength**
Grip strength of tips	1.84 lbf
Palmar grasp strength	2.60 lbf

Table 3-1 shows performance parameters for the body powered Exo-Glove. Two types of gripping forces are checked in case of healthy muscles actuated AT. Power grip uses entire hand and is related with vigorous exertions while the pinch grip requires the thumb tip and index or middle finger tip and is related to pointed grips [42]. The values of force obtained for both the force types are mentioned in the above table that is 8.2N for a pinch grip and 11.6N for a power grip. The amount of these forces are enough to carry out most of the tasks of ADL that are mentioned in [43], [44]. Forces produced by this assistive glove lie within the range of those mentioned in [9]. To make sure that involuntary forces by human hand do not interfere while doing the experiment a model hand was placed in the Exo-Glove to recheck the forces produced and it shows a very little difference as compared to the previous one involving human hand. Slight difference in values is due to the fact that the model hand does not involve many features of the human hand like stiffness of the phalange joints and therefore it doesn't apply any stress against the direction of tendon force application. Figure 3-1 shows a device which is used for measuring the pinch forces at the finger tips at few equidistant angles. Model hand was used for this purpose. When index finger rotates by the applied force from differential it changes normal angle direction and the normal direction of distal pad of index finger also changes. Magnitude of forces was calculated using a force

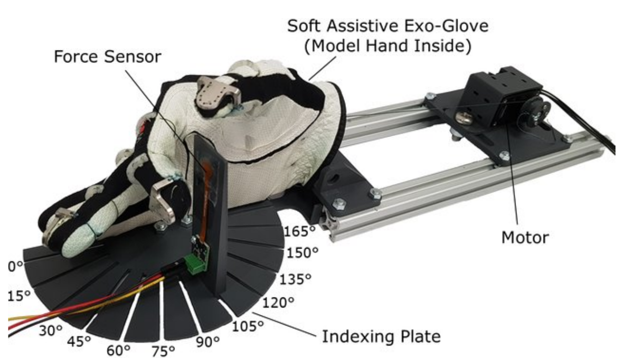


Figure 3-1: A device used to measure pinch forces at different angles at 15^o offset. courtesy: GEREZ et al.

sensor at the finger's distal pad position. Forces rise from 10 N at the angle of 0^O and reaches the maximum value of 48 N at 90^O. Moving for further angles the value of force starts decreasing and ends at 20^O.

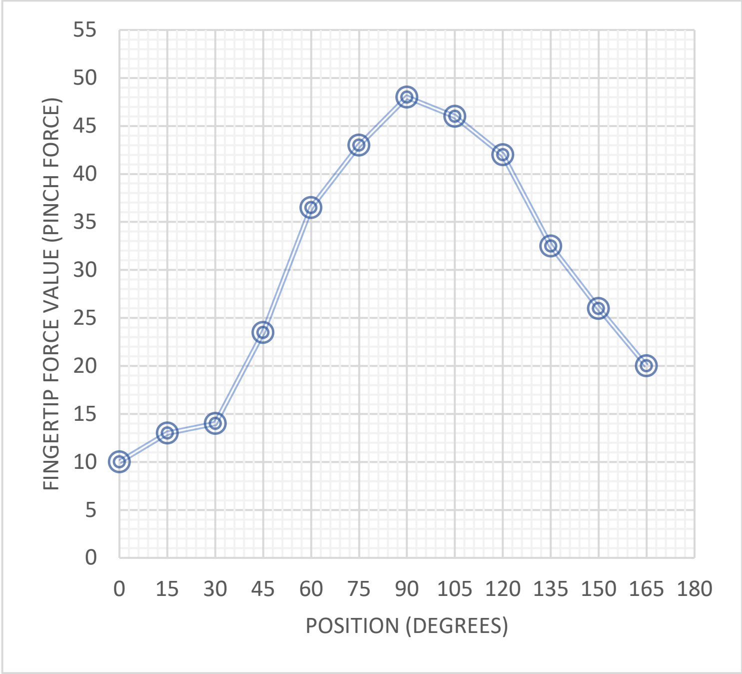
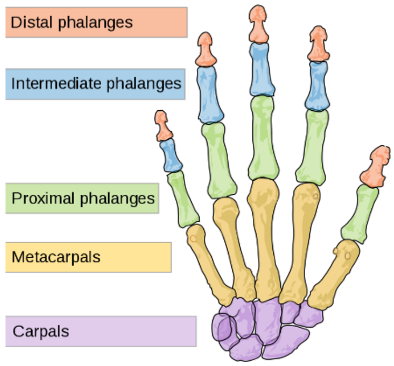


Figure 3-2: Fingertip forces at different angles

Figure 3-2 shows a plot in which forces are plotted against position of the fingertip and it shows that maximum pinch force is applied at the position of 90^O. Another experiment is also carried out to track the profile of bending fingers. The bending profile for fingers is shown for two cases: one case is when finger is in free motion and the other case is when finger is assisted by the glove. The results show that in both the cases bending profile is the same for finger motion. This demonstration was done with the help of tracking technology using high resolution devices by the research group in [1]. It captured the motion and bending profile of finger in both the cases. The design of glove makes an impact by changing the flexing contour for finger. finger joints demonstrate same contours with body powered Exo-Glove as in free style motions but fingertip shows a considerable difference in bending profile. The Exo-Glove is creating a different bending profile because it restricts the finger at certain angle to bend further but it doesn't affect the benefits of Exo-Glove which it has in assistance of hand deprived of motions used to carry out tasks of ADL.



4. Ratchet controlled Assistive Device 1.0

In this section a ratchet-controlled body powered Exo-Glove Assistive device is proposed for the purpose of lab demonstration and assessment of assistive devices that are totally mechanical. The Exo-Glove Assistive device was developed as simple as possible and it consists of the following parts.

- Fabric based glove with elastic material inside and firm outer surface. The outer surface should be such that the forces should transmit rigidly to the end points of fingers. For this purpose, the material was chosen very carefully to confirm these conditions.
- Fabric was predominantly porous to allow proper aeration and it fulfilled the conditions of transmission of forces with minimal losses.
- A ratchet mechanism with a lever (pawl) and a button to engage or disengage the lever with the ratchet pulley inside the mechanism.
- Thread based thick tendon wires were used that had high force bearing properties.
- Velcro straps to hold the ratchet mechanism device with the arm of the user.

The ratchet mechanism cost around 10 USD and glove cost around 6 USD. A bundle of thread for tendon wire cost around 4 USD from which only three meters of thread was used. The Exo-Glove works by engaging ratchet wither with the healthy hand or someone's assistance. The tendon wires are routed along the hand and are pretensioned while wearing. Tendon tensioning is achieved with the help of this method. The pretensioned tendons require less force from ratchet to pull the tendon with the considerable force. Tendons were attached only to thumb, index and middle fingers as all the necessary tasks of ADL can be executed with the help of these three fingers alone. Using this setup, the different items of household can be easily grasped. Tendon routing needs fixtures and anchors for performing necessary force of grasp with the help of ratchet device. For proper gripping and considerable angle of rotation of fingers for achieving required bending profile the position of anchor placement plays a vital role. The anchors are placed in such a way that the torque production is maximum at the point of application and the points are chosen such that while gripping the object the tendons does not cause hurdle in gripping the objects. Tendons are therefore placed along the periphery of the hand and fingers. Trial and error method was used to achieve the best possible solution for the tendon routing and maximum area of contact was achieved with the objects. The next page shows the soft Exo-Glove that was utilized for carrying out the assessments of Assistive device for grasping performance evaluation. The idea of soft Exo-Glove was undertaken by considering comfort of operation for the end user and keeping in mind the easy reproduction of Exo-Glove. Also, the said assistive device for demonstration was developed by keeping in mind easy availability of the material required to replicate it. The ratchet mechanism however needs improvement in design and functionality.

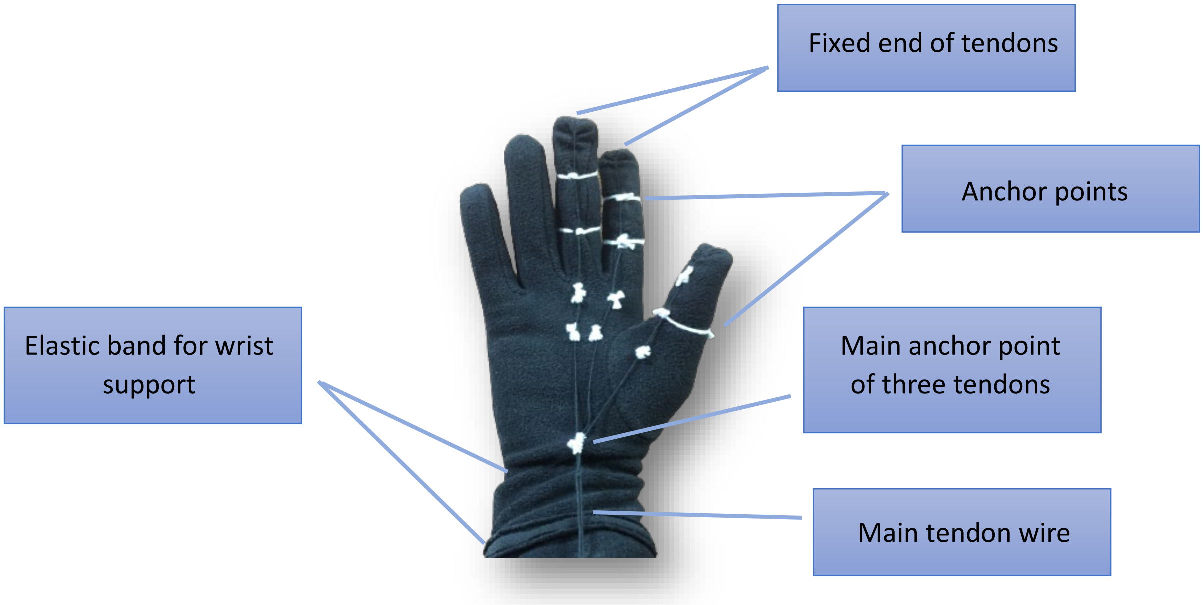


Figure 4-1: Ratchet controlled Soft Assistive Exo-Glove device 1.0

I. The Ratchet Device

The ratchet mechanism consists of a simple device available in the market that was utilized for the purpose of demonstration. The device is used for clamping purposes but it was modified to be used as a differential to transmit forces from healthy body part to the hand and fingers.

The device consists of two circular ratchet wheel pulleys and two linear wings with V shaped teeth engraved on it linearly. The linear wings move when wheels rotate and is locked with the help of lever pawl. The motion is constrained in one direction which helps while applying the force. The locking lever is also loaded with spring to push it back for locking when the button is set free. Between two linear wings a spring is loaded to push the linear ratchet away from each other.

II. Exo-Glove

For this demonstrative study a soft Exo-Glove was used. The soft glove was made for best fitting on hand (to keep the glove tight in place for effective transmission of forces). The fabric of glove was chosen such that the hand doesn't sweat too much and it allowed proper airflow with micro-level holes in the fabric. The main anchors were placed at the tips of the three fingers (Thumb, Index and middle) and wires were fixed at these points. The routing anchors were placed at different points on the hand and across the three fingers. The friction of inner surface of the glove is enough to ensure the firm grip of items with the Exo-Glove. The main benefit of using thick threaded tendon wires is that they ensure safety for use with the patient's hand and avoid any unexpected injury that may occur. The plan for actuating only three fingers is based on guidelines given by research group of Yale University that these three fingers can be effective in carrying out most of the tasks of ADL. The weight of the glove as measured was only 22 g which is way too much less than many mechanically controlled Body powered assistive soft gloves found in literature. The tendon routing was made according to the hand profile and passed through anchors on each finger. The three tendons then combined were passed through a main anchor placed near hand wrist joint (between Thenar and hypothenar region). The bending profile of each finger was checked by applying force on each finger separately with the help of tendon wire attached with it. Three tendons after being passed from main anchor were routed to the ratchet device and firmly attached to the extension of wing. The soft anchor points made up of fabric were used in this Exo-Glove which ensure safety of operation and improve hand sensibility for more efficient grasp of items. Another benefit of using fabric-based tendons was that overall weight is reduced and a lightweight setup is ensured.

The ratchet controlled assistive Exo-Glove works by engaging the ratchet mechanism. when the ratchet mechanism is pulled by an external force, the main tendon is pulled. The main tendon wire is attached with the device in tension and firmly so that a little force application from ratchet device is enough to pull the main tendon effectively. The wires allowed the transfer of force without any hurdle and with negligible friction and force losses. The main tendon wire then applies force on tendon wires passing though fingers. Finally, the force reaches to the fixed end of the fingers and this application of force on fingers move them in bending motion. Flexion is achieved with these forces and three fingers bend to grip the items easily. The anchors placed on the hand ensure that the wires passing though hand and fingers remain along the surface of the hand. This thing ensures smooth operation and wires do not cause hurdle in gripping the object.

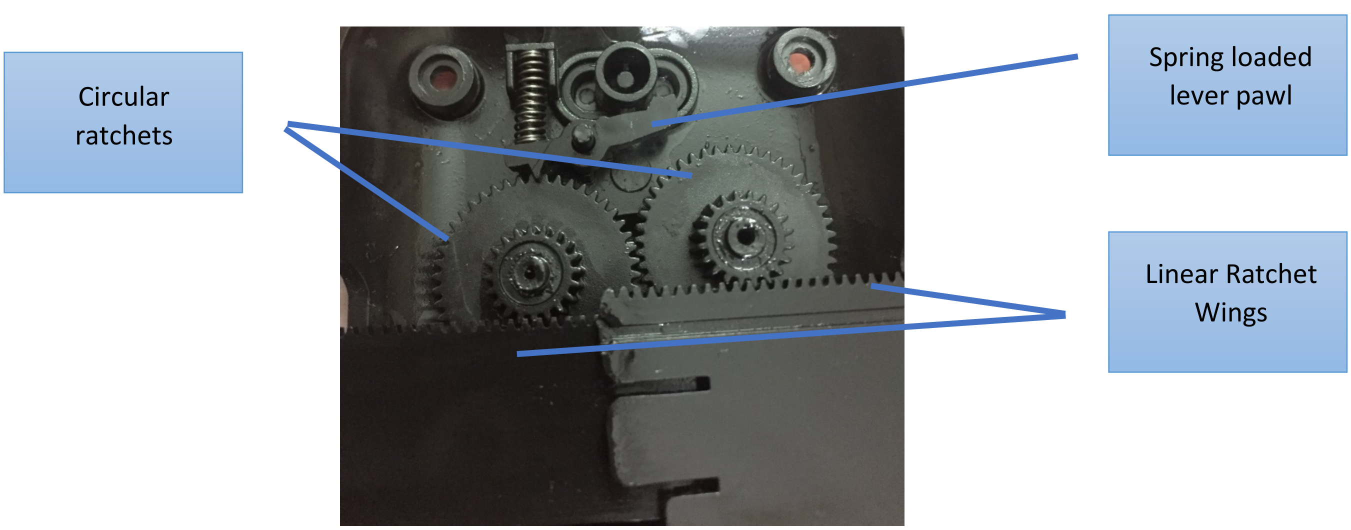


Figure 4-2: The ratchet combination device used for Exo-Glove.

The ratchet device can be worn on the forearm by user and is easy to be replaced for any other location as per user's will and need. The device was tested while wearing on the forearm. The change of location will not affect the device actuation and force transmission because anchors can be placed along the way of tendon wires routed throughout the body till the hand. The tendons are already placed in the tensioned position which works as tendon tensioning adjustment mechanism proposed by GEREZ et al in [1]. After the actuation of ratchet mechanism, the fingers are flexed and remain in that position unless user wants to disengage the mechanism by pressing the button on the ratchet device. The button actually pulls the lever pawl away from circular ratchet device and spring-loaded linear ratchet wings move away from each other releasing the force and relaxing the tensioned tendon.

IV. Grasping Performance

Figure 4-3: The assistive device was checked by its ability to grip different types of items: a) a lotion bottle, b) a tennis ball, c) an iron, d) a starch spray bottle, e) a glass full of water, f) a cold drink bottle (1.5L)

The grasping performance of ratchet-controlled Exo-Glove was checked by wearing the Exo-Glove and trying to grasp the items used in ADL. The items grasped were of different shape and weight and the Exo-Glove assistive device enabled to grasp the items effectively and with ease. Figures of items grasped are shown below for the record and videos were also recorded for each item separately which are uploaded on the google drive link given at the end.

V. Load Bearing Tests

In Figure 4-3 few items are shown for which the Exo-Glove was tested to grasp effectively. The goal of this test was to perform the grasping capability evaluation of this Assistive device made with ratchet mechanism and soft Exo-Glove. When the ratchet mechanism is engaged in locked position the items can be held in hand without any slippage or without any problem as the force being applied from the ratchet mechanism remains constant due to locking position. In this section device was tested for its ability to bear load. The weight was lifted with the help of Exo-Glove on and the values were recorded. the involuntary human hand forces were tried to minimize as much as possible by keeping the hand free and only allowing the forces from tendons to pull the Exo-Glove with interference. The items grasped with the help of Exo-Glove on had different weights which are listed below for the record.

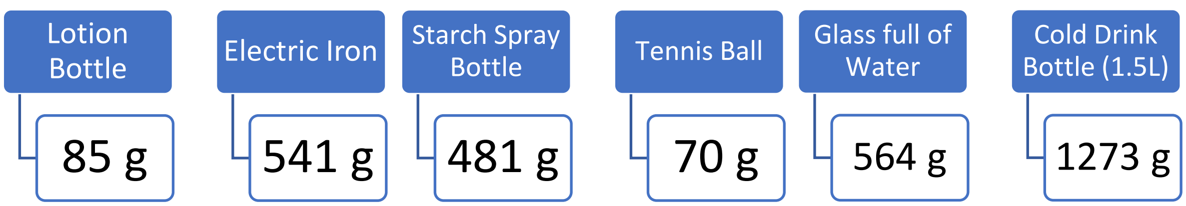


Figure 4-4: Weights of the items which were used to evaluate grasping

The Exo-Glove was also tested for lift weight bearing in which user wearing Exo-Glove was holding a bag in which wights were added subsequently and checked if the setup can bear the weight and whether the force is enough to hold the bag with increased weight. Load range of different varying weights were applied which were ranging from few grams to few lbs. When the weight limit reached to the value of 3.32 lbs. the grip couldn't be maintained and force of tendons was not enough to hold the bag in place. In other words, the load beyond 3 lbs. (≈1360 g) was unable to be withstand (roughly 13 N force). The weight bearing capacity was assessed with the help of a digital weighing scale. Figure 4-4 shows the weights of different items being held while evaluating the grasping capability of the Exo-Glove.

VI. Grasp Force

The weight scale was modified with the help of a structure attached to it so that it could measure the force applying capacity of the fingers. The setup worked like the grip strength dynamometer and it helped in analyzing the forces applied by fingers in different positions. In this evaluation forces were checked only for index finger which could be used as a generalized model for all three fingers involved in the evaluation. The forces which index finger produced ranged from 0.46 lbs. to 2.96 lbs. which is roughly an average of 7.6 N and that is fairly enough to hold low mass objects used in tasks of ADL. Although the value has a chance of error but still it gives an idea of how much force the Exo-Glove is able to provide for grasping motions by producing finger flexion.

Figure 4-5: force measurement using a modified weight scale to act as a grip strength dynamometer

The device utilized for measurement of force produced by the Exo-Glove in the index finger is a modified setup in which a weight measurement scale is mounted on a structure which allows index finger to exert force separately on the scale. In this way forces can be recorded with this setup. Figure 4-5 shows the setup used for forces measurement and a side view is also showed to have an idea how was this setup utilized in force measurement.

VII. Limitations of the setup

The ratchet-controlled Exo-Glove assistive device was designed to be as simple as possible and is the cheapest solution among all the mechanical body powered assistive Exo-Gloves present in the market. The above-mentioned setup was designed to assess the simple assistive device that can help in gripping motions. The weight of the ratchet mechanism is 61 g which is very less as compared to the other body powered assistive solutions in the literature. The mechanism is not at all perfect as there is always room for improvement and betterment but it can be consequently improved by constantly improving the components used in it. In this setup user has to engage the ratchet mechanism (actuate it) by either using their healthy hand or with the assistance of someone else they can rely on which is clearly a major limitation of this setup. The grip force is also up to a certain limit and cannot go beyond that limit as compared to those motorized devices found in literature and available for the end user as well so the results are not comparable to those devices at all. Ratchet mechanism is not as effective as it needs to be when considering its usage for assistive devices. The actuation mechanism is arduous while keeping in mind usage by stroke or differently abled people. Setup needs to be improved such that small body movements can be helpful in actuating the mechanism effectively and efficiently. The tendon routing can be improved to have the effective force transmission by using high quality tenon wires with tubes to enclose the wires so that they may function without having interreference by the items grasped in hand. The grasping of items needs maximum area of contact for effective grip forces which can be achieved by using the internal cables inside the glove. Two layered gloves should be manufactured for this purpose to route the tendon wires between both the layers which will not only remain independent in force transmission but also avoid any interference with the items being gripped. The reason for choosing this soft Exo-Glove was only that the demonstration for assistive device was being planned for which a setup was proposed which was not only easily available but also cheap and can be reproduced at any level at any place. The setup does not form any basis for building assistive devices that can be generalized but is itself based on guidelines provided by many high-quality research publications present in the literature. The ratchet mechanism was chosen to be this one because of its low cost and also easy availability and an effective demonstration could have been performed with it. Apart from its benefits the ratchet device is not up to the mark for this setup because of the difficult procedure of actuation and engagement in this setup. Also, the mechanism takes unnecessary space on the forearm and if it is optimized it can be easily placed on any place on the arm as per demand and will of the user.

5. Conclusions and Future directions

The human hand is the most important body part used to carry out multiple tasks in ADL and it's important to have an effective assistive device for those who are impaired and unable to utilize their hands properly and for this purpose a simple, effective, portable and lightweight assistive device was selected and evaluated based on its performance and ability to perform necessary tasks and to check whether it fulfils all the design requirements that are being generalized in many research publications. The device is fully able to assist those who have impaired hand motion and can be used without any problem and any external help form a person.

The most beneficial aspect of the device is that it can be used autonomously and does not require any power source to operate which proves that the device is very simple and effective. The assistive device is evaluated based on general requirements that is published in many research papers and mostly all conditions are met with this device.

Most of the devices described in literature are motor powered and heavy and require extra effort to be carried. The **device evaluated** in this study is one the lightest assistive device known yet. One of the most important point to highlight here is that the differential mechanism is usable for any hand dimension. The only customization is required for harness and glove which will cost very minimal amount. evaluation of body powered Exo-Glove shows that the device is following almost all the design criteria suggested by many extensive researches performed for defining the design requirements for Exoskeleton hand devices.

The device proposed in [1] is evaluated to be very effective in performing grasping motions in hands by bending of fingers in flexion motion. The body powered Exo-Glove can be effectively utilized for increasing the grasping capacity in the patients along with assisting the disabled (stroke patients etc.).

The evaluation of the mentioned assistive device was based on the results of the experiments performed by the research group of GEREZ et al and it was compared with the standards set by different research studies in the literature. The standards which are required to achieve an effective grip motions in patients. The evaluation in this study showed that the assistive device can be efficiently utilized for enhancing grasping capabilities. Another benefit of this device is that it is lightweight, affordable by many and last but not the least it's easy to operate. The differential mechanism proposed by GEREZ et al in [1] is very efficient in transmission of forces. Most of all the user can train with this device by staying at home and lengthy trainings are not at all required in this setup. As the developers mentioned that this device and the components are 3D printed which shows that the device does not require traditional manufacturing techniques to be developed and is very cost effective because of this.

The device can be a very effective solution for poor and needy people and also for those who are suffering from war calamities. The device is also able to be augmented with prosthetic or artificial hands and that solution can help many those people who are only suffering from loss of hand or arm but are healthy in terms of mind and nervous system. The device requires an external force to be applied and user has to apply that force with a healthy muscle motion but in many cases people might not be able to apply that force and for such a case this device is able to be augmented with a motorized actuators and the same force which is applied with the help of healthy muscle can be alternatively applied with the help of using a sophisticated motor setup but then the systems will not remain fully autonomous as is the case in body powered mechanism.

The other part was a demonstration of simplest possible assistive Exo-Glove that can be developed with the cheapest components available easily. It was undertaken to assess the performance of the simplest possible assistive device for grip motions. The device as obvious from experiment results is able to perform the gripping motion and was able to grasp daily life objects while wearing the Exo-Glove. Grasping strength and force produced by ratchet device is very limited but can be improved further by improving the control technique and optimizing the ratchet mechanism.

The future direction is to take this further in to research and propose an optimized solution for the fully body powered Exo-Glove assistive device. The device should acquire very less space and should require minimal forces for the actuation. The aim to design a ratchet controlling mechanism that can be used as an autonomous device and can be as small in size as possible and also the whole setup should be portable and very easy to carry. The plan will be to keep in mind that the end user can use the device very easily.

In the later setup (Ratchet controlled assistive Exo-Glove) the improvement is needed as mentioned in section 4 part IV. Overall the design study will be carried out on CAD modelling and a prototype will be 3D printed and will be assessed based on guidelines given by many research studies on design criteria of soft Exo-Gloves for assistance tasks in ADL like the one being proposed by [45].

References

[1] L. Gerez, J. Chen, and M. Liarokapis, “On the Development of Adaptive, Tendon-Driven, Wearable Exo-Gloves for Grasping Capabilities Enhancement,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 422–429, 2019, doi: 10.1109/LRA.2019.2890853.

[2] K.-S. Hong and J. L. Saver, “Quantifying the value of stroke disability outcomes: WHO global burden of disease project disability weights for each level of the modified Rankin Scale.,” *Stroke*, vol. 40, no. 12, pp. 3828–3833, Dec. 2009, doi: 10.1161/STROKEAHA.109.561365.

[3] A. Rahman and A. Al-Jumaily, “Design and Development of a Bilateral Therapeutic Hand Device for Stroke Rehabilitation,” *Int. J. Adv. Robot. Syst.*, vol. 10, no. 12, p. 405, 2013, doi: 10.5772/56809.

[4] H. T. Hendricks, J. van Limbeek, A. C. Geurts, and M. J. Zwarts, “Motor recovery after stroke: a systematic review of the literature.,” *Arch. Phys. Med. Rehabil.*, vol. 83, no. 11, pp. 1629–1637, Nov. 2002, doi: 10.1053/apmr.2002.35473.

[5] C. Sollerman and A. Ejeskär, “Sollerman hand function test. A standardised method and its use in tetraplegic patients.,” *Scand. J. Plast. Reconstr. Surg. hand Surg.*, vol. 29, no. 2, pp. 167–176, Jun. 1995, doi: 10.3109/02844319509034334.

[6] C. I. Mavrogiannis, M. V Liarokapis, and K. J. Kyriakopoulos, “Quantifying anthropomorphism of robot arms,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 4084–4089, doi: 10.1109/IROS.2015.7353954.

[7] B. B. Kang, H. Lee, H. In, U. Jeong, J. Chung, and K.-J. Cho, “Development of a polymer-based tendon-driven wearable robotic hand,” in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 3750–3755, doi: 10.1109/ICRA.2016.7487562.

[8] V. Mathiowetz, N. Kashman, G. Volland, K. Weber, M. Dowe, and S. Rogers, “Grip and pinch strength: normative data for adults.,” *Arch. Phys. Med. Rehabil.*, vol. 66, no. 2, pp. 69–74, Feb. 1985.

[9] C.-Y. Chu and R. M. Patterson, “Soft robotic devices for hand rehabilitation and assistance: a narrative review.,” *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 9, Feb. 2018, doi: 10.1186/s12984-018-0350-6.

[10] E. S. Lawrence *et al.*, “Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population.,” *Stroke*, vol. 32, no. 6, pp. 1279–1284, Jun. 2001, doi: 10.1161/01.str.32.6.1279.

[11] G. Kwakkel, B. J. Kollen, J. van der Grond, and A. J. H. Prevo, “Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke.,” *Stroke*, vol. 34, no. 9, pp. 2181–2186, Sep. 2003, doi: 10.1161/01.STR.0000087172.16305.CD.

[12] N. K. Latham *et al.*, “Occupational therapy activities and intervention techniques for clients with stroke in six rehabilitation hospitals.,” *Am. J. Occup. Ther. Off. Publ. Am. Occup. Ther. Assoc.*, vol. 60, no. 4, pp. 369–378, 2006, doi: 10.5014/ajot.60.4.369.

[13] G. Nelles, W. Jentzen, M. Jueptner, S. Müller, and H. C. Diener, “Arm training induced brain

plasticity in stroke studied with serial positron emission tomography.," *Neuroimage*, vol. 13, no. 6 Pt 1, pp. 1146–1154, Jun. 2001, doi: 10.1006/nimg.2001.0757.

[14] G. B. Prange, M. J. A. Jannink, C. G. M. Groothuis-Oudshoorn, H. J. Hermens, and M. J. Ijzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke.," *J. Rehabil. Res. Dev.*, vol. 43, no. 2, pp. 171–184, 2006, doi: 10.1682/jrrd.2005.04.0076.

[15] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation.," *J. Neuroeng. Rehabil.*, vol. 11, p. 3, Jan. 2014, doi: 10.1186/1743-0003-11-3.

[16] D. S. Nichols-Larsen, P. C. Clark, A. Zeringue, A. Greenspan, and S. Blanton, "Factors influencing stroke survivors' quality of life during subacute recovery.," *Stroke*, vol. 36, no. 7, pp. 1480–1484, Jul. 2005, doi: 10.1161/01.STR.0000170706.13595.4f.

[17] B. Radder *et al.*, "User-centred input for a wearable soft-robotic glove supporting hand function in daily life," in *2015 IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2015, pp. 502–507, doi: 10.1109/ICORR.2015.7281249.

[18] S. Demain *et al.*, "Assistive technologies after stroke: self-management or fending for yourself? A focus group study.," *BMC Health Serv. Res.*, vol. 13, p. 334, Aug. 2013, doi: 10.1186/1472-6963-13-334.

[19] A.-M. Hughes *et al.*, "Translation of evidence-based Assistive Technologies into stroke rehabilitation: users' perceptions of the barriers and opportunities.," *BMC Health Serv. Res.*, vol. 14, p. 124, Mar. 2014, doi: 10.1186/1472-6963-14-124.

[20] M. Fontana, A. Dettori, F. Salsedo, and M. Bergamasco, "Mechanical design of a novel Hand Exoskeleton for accurate force displaying," in *2009 IEEE International Conference on Robotics and Automation*, 2009, pp. 1704–1709, doi: 10.1109/ROBOT.2009.5152591.

[21] M. A. Delph, S. A. Fischer, P. W. Gauthier, C. H. M. Luna, E. A. Clancy, and G. S. Fischer, "A soft robotic exomusculature glove with integrated sEMG sensing for hand rehabilitation," in *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, 2013, pp. 1–7, doi: 10.1109/ICORR.2013.6650426.

[22] M. Nilsson, J. Ingvast, J. Wikander, and H. von Holst, "The Soft Extra Muscle system for improving the grasping capability in neurological rehabilitation," in *2012 IEEE-EMBS Conference on Biomedical Engineering and Sciences*, 2012, pp. 412–417, doi: 10.1109/IECBES.2012.6498090.

[23] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Rob. Auton. Syst.*, vol. 73, pp. 135–143, 2015, doi: https://doi.org/10.1016/j.robot.2014.08.014.

[24] H. K. Yap, J. H. Lim, F. Nasrallah, and C.-H. Yeow, "Design and Preliminary Feasibility Study of a Soft Robotic Glove for Hand Function Assistance in Stroke Survivors.," *Front. Neurosci.*, vol. 11, p. 547, 2017, doi: 10.3389/fnins.2017.00547.

[25] C. Partridge *et al.*, "Is dosage of physiotherapy a critical factor in deciding patterns of recovery from stroke: a pragmatic randomized controlled trial.," *Physiother. Res. Int. J. Res. Clin. Phys. Ther.*, vol. 5, no. 4, pp. 230–240, 2000, doi: 10.1002/pri.203.

[26] M. Lee, M. Rittenhouse, and H. Abdullah, "Design Issues for Therapeutic Robot Systems: Results

from a Survey of Physiotherapists," *J. Intell. Robot. Syst.*, vol. 42, pp. 239–252, 2005, doi: 10.1007/s10846-004-7194-y.

[27] J. A. Martinez, P. Ng, S. Lu, M. S. Campagna, and O. Celik, "Design of Wrist Gimbal: a forearm and wrist exoskeleton for stroke rehabilitation.," *IEEE Int. Conf. Rehabil. Robot.*, vol. 2013, p. 6650459, Jun. 2013, doi: 10.1109/ICORR.2013.6650459.

[28] B. Cherian, C. Dominic, G. Vysakh, and K. Vishakh, "Exo-Glove: A Soft Wearable Robotic Hand for Stroke Survivors," 2018.

[29] C. N. Schabowsky, S. B. Godfrey, R. J. Holley, and P. S. Lum, "Development and pilot testing of HEXORR: Hand exoskeleton rehabilitation robot," *J. Neuroeng. Rehabil.*, vol. 7, no. 1, 2010, doi: 10.1186/1743-0003-7-36.

[30] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M. C. Carrozza, "Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 5, pp. 884–894, 2012, doi: 10.1109/TMECH.2011.2144614.

[31] M. Cempini *et al.*, "Kinematics and design of a portable and wearable exoskeleton for hand rehabilitation," 2013, doi: 10.1109/ICORR.2013.6650414.

[32] C. Ockenfeld, R. K. Y. Tong, E. A. Susanto, S. K. Ho, and X. L. Hu, "Fine finger motor skill training with exoskeleton robotic hand in chronic stroke: Stroke rehabilitation," 2013, doi: 10.1109/ICORR.2013.6650392.

[33] D. Marconi, A. Baldoni, Z. McKinney, M. Cempini, S. Crea, and N. Vitiello, "A novel hand exoskeleton with series elastic actuation for modulated torque transfer," *Mechatronics*, vol. 61, pp. 69–82, Aug. 2019, doi: 10.1016/j.mechatronics.2019.06.001.

[34] O. Sandoval-Gonzalez *et al.*, "Design and development of a hand exoskeleton robot for active and passive rehabilitation," *Int. J. Adv. Robot. Syst.*, vol. 13, no. 2, May 2016, doi: 10.5772/62404.

[35] P. Rea, "On the Design of Underactuated Finger Mechanisms for Robotic Hands," in *Advances in Mechatronics*, H. Martinez-Alfaro, Ed. Rijeka: IntechOpen, 2011.

[36] J. T. Belter and A. M. Dollar, "Novel differential mechanism enabling two DOF from a single actuator: Application to a prosthetic hand," in *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, 2013, pp. 1–6, doi: 10.1109/ICORR.2013.6650441.

[37] G. P. Kontoudis, M. V Liarokapis, A. G. Zisimatos, C. I. Mavrogiannis, and K. J. Kyriakopoulos, "Open-source, anthropomorphic, underactuated robot hands with a selectively lockable differential mechanism: Towards affordable prostheses," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 5857–5862, doi: 10.1109/IROS.2015.7354209.

[38] H. K. Yap, J. H. Lim, F. Nasrallah, J. Cho Hong Goh, and C.-H. Yeow, "Characterisation and evaluation of soft elastomeric actuators for hand assistive and rehabilitation applications.," *J. Med. Eng. Technol.*, vol. 40, no. 4, pp. 199–209, 2016, doi: 10.3109/03091902.2016.1161853.

[39] I. M. Bullock, J. Z. Zheng, S. De La Rosa, C. Guertler, and A. M. Dollar, "Grasp frequency and usage in daily household and machine shop tasks.," *IEEE Trans. Haptics*, vol. 6, no. 3, pp. 296–308, 2013, doi: 10.1109/TOH.2013.6.

[40] U. Jeong, H. In, H. Lee, B. B. Kang, and K.-J. Cho, “Investigation on the control strategy of soft wearable robotic hand with slack enabling tendon actuator,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 5004–5009, doi: 10.1109/ICRA.2015.7139895.

[41] M. Xiloyannis, L. Cappello, D. B. Khanh, S.-C. Yen, and L. Masia, “Modelling and design of a synergy-based actuator for a tendon-driven soft robotic glove,” in *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2016, pp. 1213–1219, doi: 10.1109/BIOROB.2016.7523796.

[42] B. G. de Monsabert, J. Rossi, E. Berton, and L. Vigouroux, “Comparison of muscle loadings between power and pinch grip tasks,” *Comput. Methods Biomech. Biomed. Engin.*, vol. 15, no. sup1, pp. 159–161, 2012, doi: 10.1080/10255842.2012.713639.

[43] P. Polygerinos, K. C. Galloway, E. Savage, M. Herman, K. O. Donnell, and C. J. Walsh, “Soft robotic glove for hand rehabilitation and task specific training,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 2913–2919, doi: 10.1109/ICRA.2015.7139597.

[44] N. Smaby, M. E. Johanson, B. Baker, D. E. Kenney, W. M. Murray, and V. R. Hentz, “Identification of key pinch forces required to complete functional tasks.,” *J. Rehabil. Res. Dev.*, vol. 41, no. 2, pp. 215–224, Mar. 2004, doi: 10.1682/jrrd.2004.02.0215.

[45] J.-M. Dávila-Vilchis, J. C. Ávila-Vilchis, A. H. Vilchis-González, and LAZ-Avilés, “Design Criteria of Soft Exogloves for Hand Rehabilitation-Assistance Tasks,” *Appl. Bionics Biomech.*, vol. 2020, p. 2724783, 2020, doi: 10.1155/2020/2724783.

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