The Soft Extra Muscle System for Improving the Grasping Capability in Neurological Rehabilitation

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Abstract—**This paper introduces the SEM Glove (Soft Extra Muscle Glove), a comfortable aid which automatically improves the grasping capability of a human independently of the particular task being performed. The technical solution partly mimics a biological solution and at the same time functions in symbiosis with the biological system. The technical invention is also applicable to other parts or regions of the human body that might need supporting forces or torques. A key feature is that a controlling and strengthening effect is achieved without the need for an external mechanical structure in the form of an exoskeleton. The paper includes a description of the physical design, the contents and the system design.**

***Keywords-** mechatronic system ; tactile sensors; artificial tendons; underactuated fingers; stroke; neurological rehabilitation; grasping capability;*

I. Introduction

Injuries to the head [1], neck [2], and the peripheral nerves [3] are frequently occurring diseases worldwide. The overall incidence pattern is not possible to define completely since many countries do not have access to an injury surveillance system. For the same reason, it is difficult to define the prevalence pattern of these kinds of injuries, but a rough estimation can be performed in most industrialized countries. It is, however, not realistic to extrapolate these figures to the emerging and developing countries due to regional differences. In contrast to many other diseases, the etiology to traumatic injuries to the head, neck and the peripheral nerves is well known. The causes are to be found mainly in accidents due to traffic, fall, violence and at leisure. Although there is an increased awareness from the society, the number of victims is still unacceptably high.

Also, with an increased aging population during the next decades, we can foresee a further increased number of falls resulting in traumatic head, neck and peripheral nerve injuries. More severe injuries show poor recovery and can be the cause of lifelong disabilities. Such injuries leave the affected person with various sensory, motor and/or autonomic defects and may be sources of problems in activities of daily living as well as occupational activities later in life. Prognosis depends on factors like grade and level of injury, the complexity of the injured tissue and age of patient [4-6]. These are the same defects and problems that occur after a patient have had a stroke [7].

A common effect of both stroke and injuries to the head, neck and the peripheral nerves is reduced manipulation and grasping capability. In Sweden, 30.000 persons per year suffer a stroke and 20.000 persons suffer a head injury [8]. A majority of those survive, but many suffer from more or less severe consequences. A very common such consequence is one-sided paresis. Our hypothesis here is that a servo assistive and comfortable glove would increase a patient's use of the traumatized hand, and hence provide intrinsic rehabilitation.

According to Statistics Sweden (SCB), a government agency that produces statistics, more than every second woman and every fifth man between the age of 75 and 84, claim that they suffer from difficulties to grasp and carry [9]. In Sweden this group amounts to 550.000 persons. There are a number of passive products aimed at helping people with reduced strength in their hands; examples are kitchen knives with specifically designed handles, keys with larger grip etc. The so called SEM Glove (Soft Extra Muscle Glove) presented here provides a much more general aid which automatically improves the grasping capability independently of the particular task being performed.

Despite efforts to highlight primary prevention, i.e. methods to avoid occurrence of disease, as the ultimate choice of activity in order to reduce the accidents, it is expected that there is a huge number of patients in the substantial need of neurological rehabilitation. Treatment of this patient group will demand that the society provides more advanced technology for neurological rehabilitation.

Thus, during the last ten years, a substantial effort has been put into the development of technological solutions considering different kinds of repair after injuries to the nervous system [6]. The primary problem of today´s neurological rehabilitation is the lack of enough advanced high tech equipment for the tertiary prevention, i.e. methods to reduce negative impact of extant disease by restoring function and reducing disease-

978-1-4673-1666-8/12/$31.00 ©2012 IEEE

related complications, of an already existing injury such as weakness of the arm or the leg. The fast development of technology innovations makes it possible to develop such equipment not only for the tertiary prevention but also for the improvement of an injury. By the interdisciplinary collaboration between clinical neuroscience and neurological engineering such advanced high-tech innovations could be developed as a routine.

Extensive research is currently done in the area of robotic grasping and manipulation. A lot of the inspiration behind the used approaches is often taken from the human grasping and manipulation capability. Examples include grasp formation inspired by Cutkosky's grasp hierarchy, learning grasps by human demonstration [10] and robotic hand or gripper design using biological inspiration taken from the human hand. In our research on the borderline between robotics and medical engineering we have found another interesting symbiosis exploiting an artificial support system together with the biological human system for enhancing human grasping performance.

Human grasping and manipulation performance is in the normal case excellent and very hard to even come close in an artificial robotic system. However, in some important cases this excellent capability is reduced due to reasons such as stroke or normal age related weakening of the neuromuscular system.

This study presents the development of a technical innovation for neurological rehabilitation aiming at the improvement of grasping capacity of the weak hand or arm. We believe the presented concept to be unique in its functional principle and design. The technical solution partly mimics a biological solution and at the same time functions in symbiosis with the biological system. The technique of this invention is also applicable to other parts or regions of the human body that might need supporting forces or torques. A key feature is that a controlling and strengthening effect is achieved without the need for an external mechanical structure in the form of an exoskeleton.

II. MATERIAL AND METHODS

A. System design

The design of the system has been made in the context of making a servo glove for the commercial market, and hence with tough requirements on manufacturing cost. Thus the aim has been to use commercially available, standardized, electronic components and materials and focusing on developing and improving the system as a whole. The main parts of the patented servo glove design [11] are:

• A uniquely designed glove which combines different textiles and textile design features to achieve the specific properties needed for the function of the glove, in particular for the transfer of forces and torques to the fingers.

• Artificial tendons, which are integrated in the glove alongside the fingers for which the grasp should be strengthened. These tendons are connected to actuators in the form of electrical motors, which via specifically designed transmission mechanisms create the required pulling forces.

• A control algorithm which is based on information from tactile sensors [12] placed in the fingertips of the glove and force sensors in the palm and which adds an automatic but adjustable servoing effect to the human grasp.

Special considerations have been made to the fact that the construction uses underactuated fingers. The movements of underactuated fingers can by definition not be controlled precisely as a fully actuated finger. Therefore the mechanics has to be designed in a way that supports grasping without explicit control. Underactuated fingers have the possibility to be low cost, not only because of few actuators, but also because less sensor information is needed. Furthermore the design does not have to be as precise as for fully actuated fingers. In order to perform anything successfully with the hand, the mechanism must be designed to adjust to the object passively — morphological computation [13].

The number of fingers that a gripper should have naturally depends on the purpose. For esthetical reasons it might be desirable to have five fingers. However, analysis complexity increases with the number of fingers. For grasping two or three should generally be enough. Two fingers that move in a plane are preferable from an analysis point of view. Schuurmans [14] has analyzed this case and optimized it with regard to graspability. One reason for having an underactuated finger is that the underactuation will provide an inherent ability to grab objects, such that less information about the grasp is needed. Therefore, manufacturing an underactuated finger has the chance of not only being simpler in terms of actuation equipment, but also in terms of sensors.

An underactuated finger (particularly the case with only one actuator) will rarely have the actuator itself integrated in the finger. Therefore, the finger does not need to have room for the actuator itself. When the actuators, typically electric motors, are to be placed on the phalanxes of the fingers, it is common for the finger to have the load carrying structure as a shell around the actuators, wiring and sensors. Another design solution is to have the load carrying structure inside in the middle and then have the equipment surrounding it. The former structure can be called an exoskeleton, which has a biological equivalence in insects and crabs while the latter can be called an endoskeleton with biological equivalence in mammals. In the SEM Glove the chosen solution is to have the actuators in a separate unit, as can be seen in Fig. 2.

Later in this paper the mechatronic parts of the design will be described in some more detail, especially concerning the requirement specification, the sensing and control aspects and finally the general control structure.

Figure 1. The glove and the connection

Figure 2. The power unit

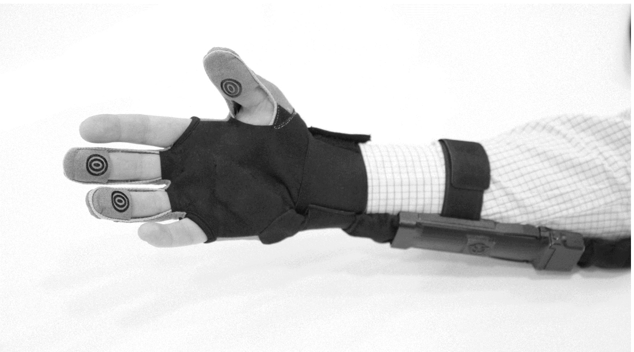

Figure 3. The glove as worn

B. Physical designs

The physical design of the glove is depicted in Fig. 1-3. The glove itself contains the sensors and the artificial tendons, whereas the motor, the actuators and the batteries are put as a separate power unit in a packet that is worn on the shoulder as a miniature backpack. The power unit and the glove are connected through a cable worn alongside the arm as shown in Fig. 3. It is possible to disconnect the glove from the packet, which makes it possible to replace a worn-out glove or to have several gloves to be worn on different occasions. The connection also makes it possible for a clinic to have several gloves in various sizes to use for different patients. The connection is easy to open and thereby shutting off the power to the glove in case of emergency. The combined weight of the glove and the power unit is around 700 g.

There are many quite specific and critical design issues related to physical design of servo gloves. These issues include:

- Textile properties (stiffness/flexibility, friction against tendons, flame safeness, and more)
- Tactile sensor requirements and availability
- Guiding and linking of tendons including tendon force measurements
- Miniaturized actuation and transmission subsystem including safety release mechanisms
- Microcontroller hardware and interface circuits.

The full paper will discuss these design issues in some more detail.

The fingers and tendons: In order to keep as much as possible of the fine motor ability of the wearer the SEM Glove has been designed with only three fingers; the thumb, the middle finger and the ring finger. The reason for this is that the wearer thus can use the forefinger without being bothered by the glove which makes it possible to form a common pinching grip to pick up small objects like coins, a movement that in most cases don’t require much muscle strength. Instead the aim is to increase the grip strength of the whole hand where the middle finger and the ring finger are of more importance.

On two sides of each finger there are wires acting as artificial tendons. The artificial tendons are made up of tightly rolled spiral wires, Boden cables, in order to minimize the friction between the textile and the wires. In order to further lower the friction the wires are made of dynema, a strong and stiff material, combined with Teflon (PTFE). The force in the tendons are restricted to 20 N which in the fingertips gives around 3-4 N, added to the force that the wearer self can produce.

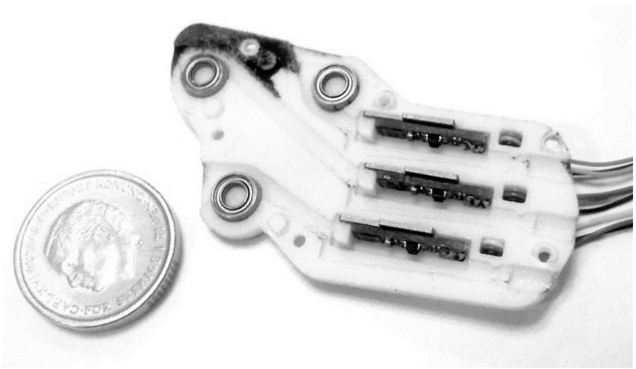

Figure 4. The force sensors used in the palm

The sensors: The SEM Glove has two types of sensors. In the finger tips there are FSR (Force-Sensing Resistors). A constant voltage of 0.3 V is applied and the current changes are measured using an OP-amp (operational amplifier). In the palm there are capacitive sensors connected to the wires in the fingers (see Fig. 4). These sensors are constructed as miniature steel beams on top of the circuit board with a small gap in-between. On the circuit board is an oscillator whose frequency depends on the capacitance between the beam and the circuit board. A microcontroller unit (MCU) is counting the pulses from the oscillator. When a force is applied to the sensor the beam is bent and the capacitance, and thus also the frequency of the oscillator, is changed. The MCU notices the change in the number of pulses and adjusts the force to the tendons. The bending of the beam is of the order of 0.01 mm and the frequency of the oscillator is between 1.1 MHz and 1.6 MHz for normal values of the force on the sensors.

The control unit: The SEM Glove is being controlled by a Reduced Instruction Set Computer (RISC) processor from ATMEL using an Asynchronous Transfer Mode (ATM) core. Via a serial port the processor can be programmed and it is possible to log measured values. This makes it possible to program the glove so that the added power to the hand grip can be adjusted individually for each wearer, depending on the different injuries and abilities. The design has been made for future possible replacement by USB communication. There is an LCD display for error messages and other information to the user.

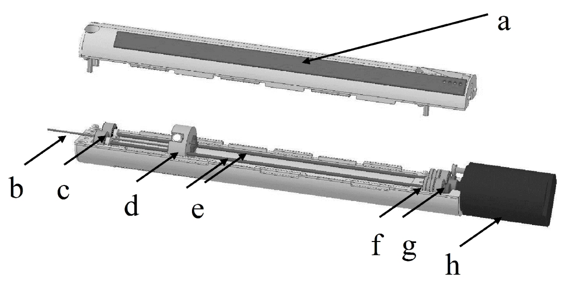

Figure 5. The actuators. a. PCB for Hall sensors, b. Steel cable, c. Bearings, d. Nut, e. Threaded bars, f. Bearings, g. Gearings, h. Motor

The motor unit: The power to the SEM Glove comes from two rechargeable 3.7 Volt lithium-ion batteries connected in series, with a total capacity of 1000 mAh. One charge gives 1-3 days of use depending on the use. The batteries run a Faulhaber DC motor. The motor is controlled by the MCU using Pulse-width modulation (PWM).

The actuators: There are three actuators of the linear kind powered by the DC brushed DC motor. The motor drives two threaded bars with standard M1 threads. A plastic nut moves as the bars rotate. On the motor side each bar is supported by one radial and one axial bearing and on the opposite side by one radial. The force generated by the actuator is transferred out of the actuator by a steel cable connected to the nut. The steel cable is relatively thin, which is possible since the actuator is designed for only pulling forces. The end positions of the nut are detected using Hall effect sensors. There are no encoders and thus only the end positions are detected. The different parts of the actuator are shown in Fig. 5.

The textile: The textiles in the SEM Glove have been chosen to be robust and dirt repellent enough to last the whole lifetime of the product. The main part of the glove is made of synthetic leather but at the fingertips and in the palm there are patches of skin with some rubber circles to improve the grip. So far a limited number of prototypes in standard sizes have been constructed, but for optimal performance the gloves should be tailor-made for the wearer.

C. Control system

The control system for the SEM glove is based on the input for the tactile sensors in the fingertips and the force sensor in the palm as well as the wearers own voluntary control of the grip. The system loop is described in Fig. 6.

III. RESULTS AND DISCUSSION

A functional SEM Glove has been introduced and presented. During the whole development phase various field tests have been made. The persons participating in these tests have been patients with either temporarily or permanently reduced grasping power.

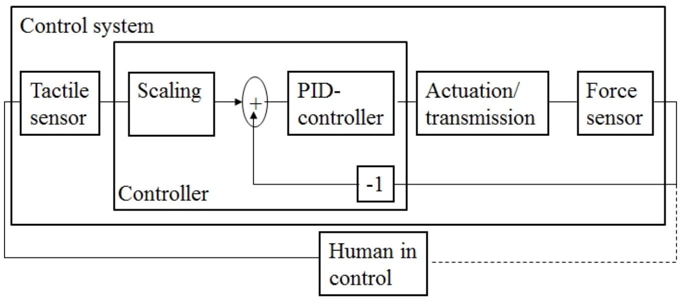

Figure 6. The control system

The first tests were made in cooperation with the Swedish Public Employment Service. Three patients in the ages of 25, 61, and 35 years, respectively, had long sick leaves due to pain in the arms following substantial work load. Activity of the arms resulted in suboptimal strength of the grasping capacity in both hands. The SEM Glove was offered the three patients. Following optimization of the individual SEM Gloves the patients evaluated the system during work for two weeks each (one of them for one month). Simultaneously, four healthy volunteers tested the SEM Glove system for various leisure activities.

The patients improved their individual grasping capacity during workload and felt comfortable with the system applied on their bodies and without any individual problems. The 25 year old female had the capacity to go back to her job as shop assistant with the SEM Glove system on each arm. The system was well tolerated in her daily activities. The 61 year old male stevedore improved his grasping capacity substantially although not to the level he had before sick leave. The 35 year old archivist felt clearly helped by the SEM Glove but wore it less frequently due to a sore elbow [15].Likewise, all of the four healthy volunteers accepted the system without having any difficulties whatsoever and were benefited of the system with regard to strengthening the hand grip during their leisure activity.

In order to further evaluate the SEM Glove from a clinical perspective a feasibility study with short-time tests on the use of the glove as an assistive tool for patients with chronically reduced grasping power has been made in cooperation with the University Department of Rehabilitation Medicine at Danderyd Hospital in Stockholm. The patients in the study did standardized tests for controlling their grip strength and fine motor ability with and without the glove on. The results are at present being evaluated and will be presented elsewhere [16]. The plan is to continue the clinical testing by doing similar systematic tests on patients in the process of recovering from a stroke.

New tests are also performed in cooperation with Swedish Public Employment Service to evaluate future design modifications of the glove.

Within the International standard ISO 9999, Assistive products for persons with disability, the SEM Glove has been classified within the following categories:

24 18 03 Devices for grasping. Products for grasping an object which replace the gripping function of the hands.

06 06 07 Hand-finger orthoses. Devices that encompass the whole or part of the hand and the whole or part of one or more fingers.

That there are many different applications for this kind of assistive technology was proved in March 2012 when General Motors and NASA presented a prototype of a similar kind of construction, a type of glove to be worn by astronauts, called the K-glove or Robo-Glove [17].

As mentioned before the aim in the development of the SEM Glove has been to use only standard components and materials. For further improvement it is desirable to use individually constructed sensors where the size and position of the sensors should be individually adjustable.

The result of the present development shows the possibility to further support disabled people with new technical innovations aiming at improvements in their daily life activities. A prerequisite is that health care staff and engineers especially from the field of engineering mechatronics merge together more actively in the search for well-designed new technical innovations which may improve disabled people in their neurological rehabilitation.

ACKNOWLEDGMENT

This work was in part sponsored by the Swedish Governmental Agency for Innovation Systems (VINNOVA) with a prize for start-up companies in 2008. Also, the developed SEM Glove system was awarded the first prize at the international competition of robotics in Sweden, Robotdalen Innovation Award 2012.

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