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State-of-the-Art of Hand Exoskeleton Systems

Report interno a cura di:

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2011

Abstract

This paper deals with the analysis of the state-of-the-art of robotic hand exoskeletons (updated at May 2011), which is intended as the first step of a designing activity. A large number of hand exoskeletons (both products and prototypes) that feature some common characteristics and many special peculiarities are reported in the literature. Indeed, in spite of very similar functionalities, different hand exoskeletons can be extremely different for the characteristics of their mechanism architectures, control systems and working principles. The aim of this paper is to provide the reader with a complete and schematic picture of the state-of-the-art of hand exoskeletons. The focus is placed on the description of the main aspects that are involved in the exoskeleton design such as the system kinematics, the actuator systems, the transmission parts and the control schemes. Additionally, the critical issues provided by the literature analysis are discussed in order to enlighten the differences and the common features of different practical solutions. This paper may help to understand both the reasons why certain solutions are proposed for the different applications and the advantages and drawbacks of the different designs proposed in the literature. The motivation of this study is the need to design a new hand exoskeleton for rehabilitation purposes.

I. Introduction

The hand is an organ of grasp as well as sensation, communication, fine discrimination and exquisite dexterity. From a kinematic point of view and according to a popular model, the human hand has 20 degrees of freedom (DOFs) [1]. In particular, the index, middle, ring and little fingers have 3 joints and 4 DOFs each. From the distal end, the joints are: the distal interphalangeal (DIP), the proximal interphalangeal (PIP), and the metacarpophalangeal (MCP) joints. The DIP and PIP joints have flexion/extension DOF, while the MCP joint has both flexion/extension and abduction/adduction DOFs. For the thumb, there are 3 joints and 4 DOFs. From the distal end, the joints are: the interphalangeal (IP), the metacarpohalangeal (MCP) and the Carpometacarpal (CMC) joints. The IP and MCP joints have flexion/extension DOF, whereas CMC joint has both flexion/extension and abduction/adduction DOFs.

Since the 80's, many researchers have been attempting to develop robotic hands aiming at replicating the functions of the human hand, and the studies presented in the scientific literature are simply uncountable. The main applications of these devices are related to industrial robotics (for the dexterous manipulation of robots), telemanipulation, humanoid robotics, and upper limb prosthetics (where the device replacing the missing hand should be intuitively controlled by the amputee).
A special kind of robotic hand is given by the hand exoskeletons (HEs), also known as active hand orthoses. With respect to the other kinds of robotic hands, a HE is an actuated mechanical system (actively controlled) that is directly attached to the human hand so that the movements of the two systems are coupled while – from the dual point of view – forces/moments are exchanged. In the design of such machines, a number of critical issues are therefore to be considered, e.g. the control of the transmitted forces is mandatory for safety reasons, the motion of the HE links must be consistent with that of the human fingers and so on. In practice the exoskeleton can apply forces to the fingers in order to force them to perform a given trajectory or to improve the force that the natural finger could normally apply. The HE can also have the function of tracking the human finger movements (the devices specifically developed for this task only, also known as data gloves, do not need actuators and thus cannot be strictly considered as HEs).
HEs could be distinguished into 3 main groups, according to the target they are devoted to:

- Rehabilitation HEs;
- Haptic devices;
- Assistive HEs.

Rehabilitation devices [2-13] are tools specifically developed to perform exercises for recovering the function lost by the hand. Haptic hands [14-24] are worn by the human hand and have two main functions: tracking the wearer's hand movements for controlling some other device and providing a force feedback to the user's hand. For the first function the haptic device must be able to measure the position of human fingers with proper position sensors. The data acquired by the haptic device are used to control the position of a slave device. The slave device could be real or virtual. If the slave device is a real device, such as a remote grasping manipulator, the haptic device is generally called "Master Hand" [14, 17, 18, 23]. On the other side, the slave device could be generated in a software simulator (virtual reality). The second function of haptic device is providing force feedback to the user's human finger. The forces measured by the real slave device or calculated from the virtual reality simulator are reflected to the operator's human fingers by means of the exoskeleton actuators. This fact causes a realistic human sensation of touch and force sensing. Assistive devices [25-29] are tools that are used by patients with hand diseases in their everyday living to perform activities that would be difficult or impossible to be carried out without a supportive aid. Assistive devices must be lightweight and comfortable because the user wears it in his everyday living. It is worth noting that these devices can be used for rehabilitation purposes as well.

Normally, a specific applications demands a specific architectures (i.e. specific mechanism, geometry and topology). For instance, according to the application of the exoskeleton, there are different numbers of DOFs for one single finger or different numbers of fingers to form the whole hand. Some exoskeletons control the motion of each finger [17, 18] or group of finger (index, middle, ring and little ones) [7, 8, 25] by 1 DOF or 2 DOFs by coupling the motion of DIP, PIP and MCP joints whereas others control the hand with up to 20 DOFs [3] by 4 DOFs per single finger. Various kind of actuators and transmission system are used. In some exoskeletons, the links are driven by means of pneumatic cylinders [10, 21, 26, 27] whereas many other systems are driven by electric motors. Usually electric motors are remotely located far from the exoskeleton joints and actuate them by transmission systems such as wire-driven mechanisms [2, 15, 18] or linkage mechanisms [28, 17]. On the other side, by using some particular kind of electrical motors (ultrasonic motors), it is possible to locate the motors in the joint (close to the joint) and directly actuate the exoskeleton [14].
In conclusion, there are different HEs which are extremely different in characteristics and architecture. The aim of this paper is providing the reader with a complete and schematic sketch of the state-of-art of HEs. The focus is placed on the description of the systems' kinematics, the actuator systems, transmission parts and control schemes in order to enlighten on the differences and provide elements for a possible HE classification.

II. Hand description

In the following, the architecture, the systems' kinematics and the control schemes of different HEs that were found in the scientific literature are synthetically described. Data gloves are not reported, although many characteristics are common with HEs, since they are not intended to actuate human hands and also systems shown in web pages but not associated with scientific papers are not considered. For those exoskeletons provided with a given name by their own developers, the given name is used (e.g. SKK [14], HWARD [7] or DLR Master Hand [17]). For the others, the affiliation of the first author is conventionally chosen to form a name, like: "University of Tokyo Hand" that was made by Hiroshi Yamaura from Tokyo University [2]. In the following, we present a selection of HEs (28 HEs). Although we find in the literature 11 more systems, here we describe the most important ones and leave reporting papers with same kinematics or architectures.

II.1. University of Tokyo Hand I

This hand rehabilitation system is suitable for patients who are suffering from contracture and paralysis [2, 30]. It contains two main components: a hand rehabilitation machine that moves the index finger of the injured hand and a data glove that is connected to the healthy hand and feeds the input data for controlling the rehabilitation machine in the so-called "self-motion control" strategy.

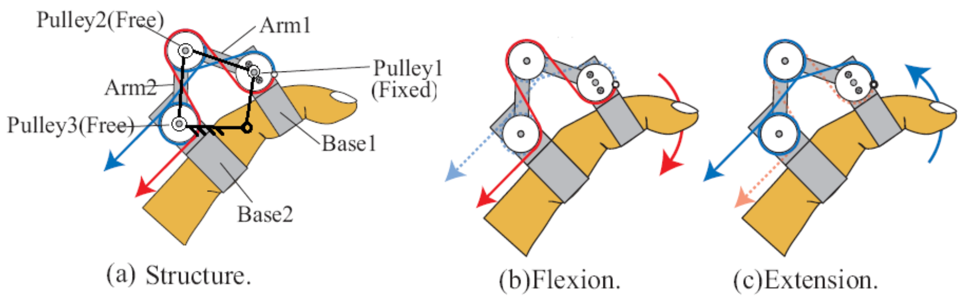


Fig 1. A popular solution for the transmitting power to the phalanges is based on a four-bar mechanism scheme (Taken from [2])

This HE controls the movement of a finger through a mechanism with 2 DOFs, where the mobility of the DIP and PIP joints is coupled. The exoskeleton moves the finger by means of 3 four-bar mechanisms. Each four-bar mechanism contains 2 external links and 2 human finger links (see Fig. 1a). Furthermore, it contains 3 external joints (2 free joints and 1 actuated pulley) and 1 human joint (DIP, PIP or MCP), as schematically represented in Fig 1.

Each four-bar mechanism could be controlled by means of an actuator directly or indirectly such as through a wire-driven mechanism (used in this HE), a connected linkage mechanism etc. In wire driver mechanism, the actuated pulley is connected to the motor by means of two wires, as shown in Fig.1; the red line represents the flexion wire, and the blue line represents the extension wire (see Fig. 1b and Fig. 1c). One end of each wire is attached to the pulley rotoidally connected to Base 1 and fixed to Arm 1, and the other end is attached to a motor. The movement of the cable leads to the rotation of the actuated pulley that results in a rotation of the human finger link.

The actuator part contains two servo motors (2 active DOFs). The MCP joint (1 DOF) is actuated by a motor through a four-bar linkage (by a scheme similar to that shown in Fig. 1a). The PIP and DIP joints are actuated by 2 coupled four-bar linkages according to the scheme shown in Fig. 2, using two wires so that these joints are actuated with another servo. Thus, this machine uses two motors to move three finger joints.

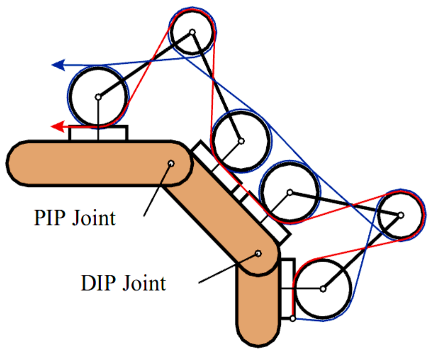


Fig. 2 Coupling between the 2 four-bar mechanisms for DIP and PIP joints (Taken from [2])

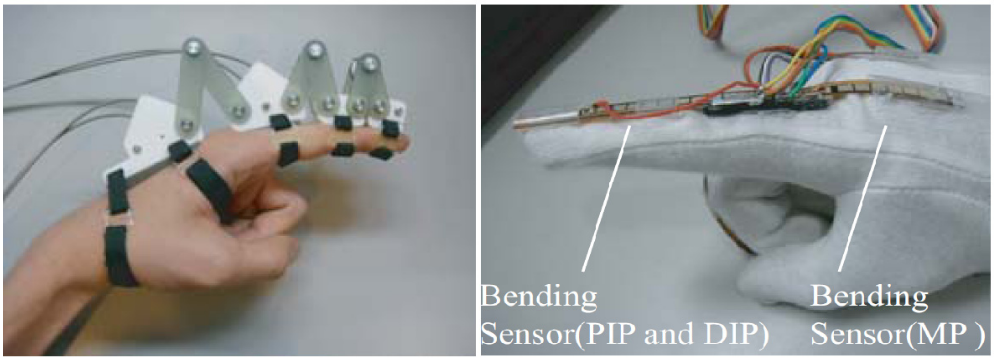


Fig. 3 University of Tokyo Hand I Exoskeleton (slave) and Data Glove (master) (Taken from [2])

Generally, hand paralysis does not affect both hands. Therefore, some hand rehabilitation systems involve the use of the unaffected healthy hand to implement the so-called “self-motion control” strategy. The hand rehabilitation process proceeds as follows: (1) the patient wears a data glove on the healthy hand; (2) the rehabilitation machine is attached to the target finger of the affected hand as shown in Fig. 3; (3) the machine is calibrated for the maximum flexion and extension of the finger; (4) the target finger joints are controlled by the finger joints on the data glove (i.e. mirror motion): the data glove system measures the angles of the MCP and PIP joints on the index finger of the healthy hand: the joint information is fed as control input to the hand rehabilitation machine, and this input controls the angles of the MCP and PIP joints on the corresponding finger of the injured hand.

The combination of wire-driven mechanism and four-bar mechanism makes it possible to achieve a wide range of joint motion and good control of finger movement. As the motors are not placed on the finger, the weight of the machine on the finger is reduced. Additionally, the chance of increasing the number of motors or using higher driver motors is available. Furthermore, due to the four-bar mechanism structure, the device can easily be attached and adjusted to different hand size. Another advantages of this hand is that the palm is free of mechanical elements, thus allowing the hand to directly interact with the environment. The control system has an important drawbacks: the motion of the hand is controlled only through position sensors and no force sensors have been used in the interface between the rehabilitation machine and the hand. Therefore uncontrolled forces transmitted to the wearer's hand could provoke dangerous situations.

II.2. Berlin University Hand

The device was designed with focus on support of the rehabilitation process after hand injuries or a stroke [3, 31, 32]. The control method exploits Electromyography (EMG) sensors located on palmer and dorsal side of the forearm.

This HE controls 20 DOFs of the human hand motion. Each finger has 4 active DOFs: flexion/extension in MCP, PIP and DIP joints; abduction/ adduction in MCP joint. The thumb also has 4 DOFs. The CMC joint is controlled by flexion/extension and by abduction/adduction movement, whereas the MCP and IP joints are controlled by their flexion movement (Fig. 4). The exoskeleton moves the finger by means of 3 four-bar mechanisms, with the same conceptual

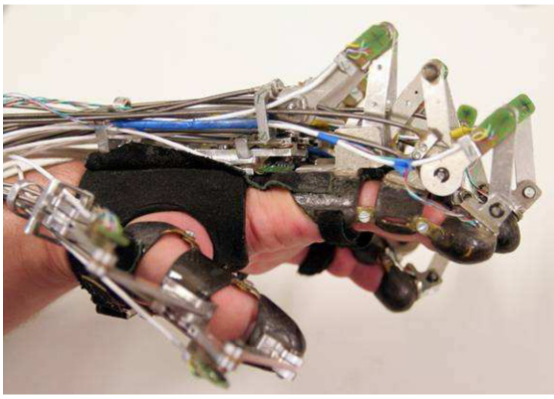


Fig. 4. Prototype of the Berlin University Hand (Taken from [3])

scheme shown in Fig.1. The joints are driven through wire-driven mechanisms. One actuator unit consists of 4 DC motors for actuating 1 finger, so that five actuator units are required for a hand. The system is equipped with 5 different kinds of sensors namely angular measurement sensors (2 types), force sensors, Electromyograph sensors and electrical current sensors. Electromyography electrodes measure the electronic activity at the skin up to 16 muscles, which is used as input for controlling the machine. To provide angular position measurements which are evaluated by integrated circuits, the angle between 2 external links in each four-bar mechanism is measured by Hall sensors (internal position sensors). On the other side, optical quadrature encoders (internal position sensors) are used to measure the angular position of the motor axes. Six force sensors (2 sensors on top and bottom of each phalange) are placed between the human finger attachments and the exoskeleton. The data that are gained from the external force sensors are used to measure the force exerted on the human fingers. The actual current of the motor is measured by means of electrical current sensors. By these current, the torques at the motor axes are computed as well. Together with this torque and mechanics of linkages, the force exerted to the phalanges could be evaluated.

This HE uses two different redundant sensors for position analysis and two different redundant sensors for force analysis. For instance, the angel between 2 external links in each four-bar mechanism are measured by 2 kinds of position sensors, one is placed on links of four-bar mechanism whereas the other is installed on the motor (encoders). It is possible to detect mechanical failure by comparing the values gained by each sensor and correct them. Detailed information about the control procedures are explained in [32].

II.3. Gifu University Hand

This hand machine was designed with focus on the rehabilitation of an injured hand by means of the self motion control strategy [4, 33]. The machine not only supports the movement of all fingers and thumb but also assist the movement of the wrist.

This rehabilitation machine controls 18 DOFs of the human hand motion. Each finger (index, middle, ring and little finger) has 3 DOFs, whereas the thumb and the wrist has 4 DOFs and 3 DOFs respectively. As shown in Fig. 5, the exoskeleton assists the flexion/extension of MCP and PIP joints by means of 2 four-bar mechanisms actuated by 2 servo motors and assist the abduction/

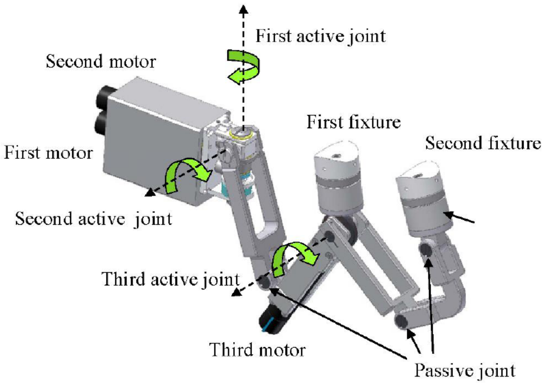


Fig. 5. Finger motion assist mechanism (Taken from [4])

adduction of MCP joint by another servo motor. The distal phalanx of the human hand is kept free and thus the DIP joint is not controlled by the machine. The exoskeleton moves the thumb by 4 servo motors. Three motors are used in 3 four-bar mechanisms which support flexion/extension of IP, MP and CM joints. Abduction/adduction movement of CM joint is assisted by a circular cone motion mechanism by a servo motor (Fig. 6). It is worth mentioning that the authors assumed that the thumb motion is a circular cone motion, in which the vertex of the cone is located in the wrist and the orientation of the thumb is almost constant with respect to the cone axis.

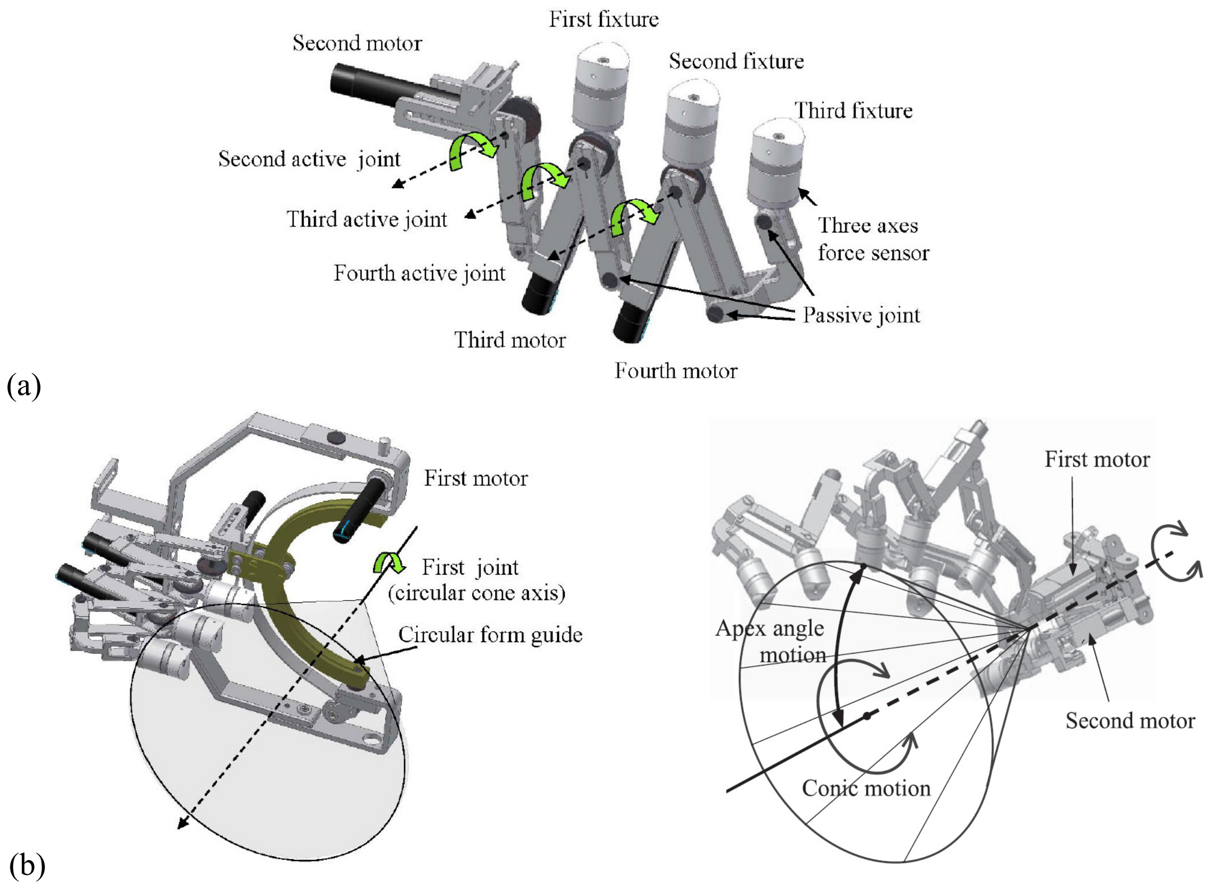


Fig. 6. Thumb motion assist mechanism: (a) Motion assist part of flexion/extension; (b) Motion assist part for thumb opposition (Taken from [4])

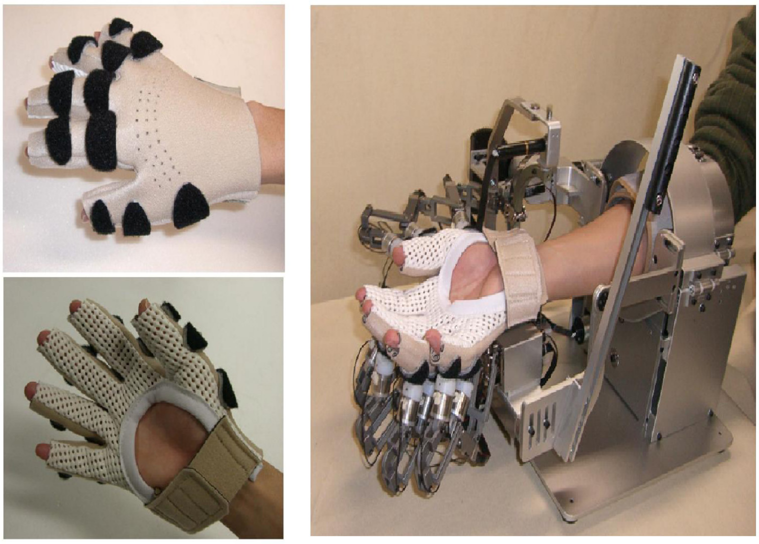


Fig. 7. A human hand fixed to the machine by a glove for the impaired hand (Taken from [4])

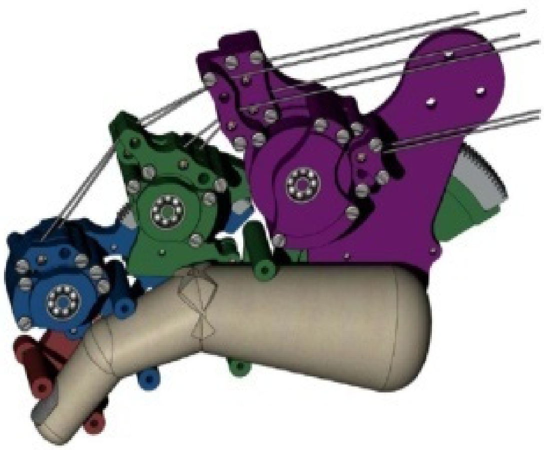
The exoskeleton is driven through a self motion control that allows the impaired hand to be driven by the patient healthy hand through the data gained by a data glove. The system is equipped with 2 different kinds of sensors, i.e. rotary encoders that are installed into the motors and 3-axes force sensors (external force sensors) that are placed between the human fingers and the exoskeleton. The data gained from the rotary encoders are used to calculate the angle of the exoskeleton joints. The movement of the HE is controlled with position controlling. The position data that are received from the data glove are fed into the control system to move the HE. The data that are gained from the force sensors are used to measure the force exerted on the human finger. To enhance the reliability of the controller, a sub CPU which keeps watching on the states of sensors, joint torques and the control CPU was added. The control CPU also watches the sub CPU. If a state is abnormal, the output of motor driver is blocked.

This hand was designed to support the movement of the hand fingers and the wrist. This HE has two main drawbacks. In addition to the data glove that the user wears in his healthy hand, the user must wear another glove for the impaired hand (Fig 7). This glove connects the human hand to the exoskeleton. Although the palm is free, this glove causes loosing the direct contact between human fingers and the object. On the other hand, the joints of the four-bar mechanisms are actuated directly by servo motors that are placed on the exoskeleton. This increases the global weight of the exoskeleton. This weight can trigger muscle fatigue in the user for repeatable rehabilitation activities.

II.4. AFX Hand

This finger exoskeleton is a rehabilitation system suitable for patient after stroke [5]. The machine was designed to support only the movement of the index finger.

The machine controls 3 DOFs of the human index finger motion. The AFX hand has a metal exoskeleton that connect the proximal, middle and distal segments of the index finger through pairs of rollers as shown in Fig. 8.



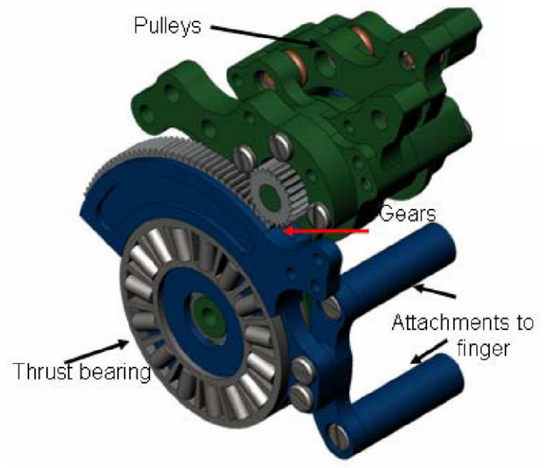


Fig. 8 AFX Hand exoskeleton (Taken from [5])

Fig. 9. Detail of a joint of AFX Hand (Taken from [5])

Cables from the DC motor actuators are attached to the pulleys which rotate the smaller gear. The larger gear is connected to the section of the exoskeleton which is attached to the human finger segments. The rotation of small gear causes the rotation of larger gear, so the group connected to the human finger phalanges rotate around constant axes (not around human finger joints). According to the configuration, the attachments to the finger (rollers) can rotate freely and move relatively to the finger phalanges, so the final motion is adjusted automatically around network joint in order to avoid mechanical interference between human finger and HE in bending.

The exoskeleton moves 3 joints of index finger by 6 servomotors (2 motors for each joint, 1 for the flexion and 1 for the extension). A wire driven mechanism is used to transmit the power to the 2 mating gears which produce joints rotation.

There are 2 kind of sensors in this exoskeleton. Firstly, there are optical encoders that are attached to the DC motors and whose data could be used to compute joint angles of exoskeleton. Secondly, the system is also equipped with internal force sensors to measure the cable tensions. As the cable is spooled from the motor, it runs over a small pulley mounted on a cantilever beam (Fig. 10). The beam is instrumented with strain gages to determine the force applied by the cable. With reference to Fig. 10, net cable tension is found by computing the difference between T_{ext} (extension force) and T_{flex} (flexion force). The joint torque can be calculated from this value with knowledge of the pulley height above the joint and the gear ratio.

Optimal conditon to control a joint in wire driven mechanism is utilizing 1 motor to actuate a joint in both directions. One concern of using two motors to actuate the same joint is the undesirable antagonism between the two motors. In order to obtain optimal performance from the two motors, the controller system designed to minimize the antagonistic effects. Additionally, the weight of 2 motors for each joint is considrable even if the actuator unit is located on the forearm.

II.5. Harbin Institute of Technology Hand

The device was designed with focus on support of the rehabilitation process after hand injuries [6, 34].

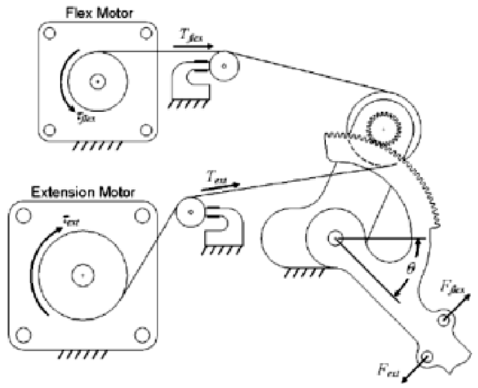


Fig. 10. Actuator unit for one joint of AFX Hand (Taken from [5])

The rehabilitation machine controls 2 DOFs of the human finger motion and is connect to the finger in 3 points. The flexion/extension movement of DIP,PIP and MCP joints are coupled and actuated by means of 1 electrical motor. The abduction/adduction of MCP joint is actuated by another DC motor.

A wire driven mechanism is used to actuate the flexion/extension of finger joints (6 wires for 1 finger). A bidirectional movement is created by looping the cables around a small pulley which has common axis with the spur gear of exoskeleton. Under the force transferred from the spur gear, the circular rack drives the finger phalanges to rotate about the finger joint as shown in Fig. 11. The abduction/adduction movement of MCP joint is actuated directly by another motor, which drives a spur gear through a pair of bevel gear and a rack as can be seen in Fig. 12.

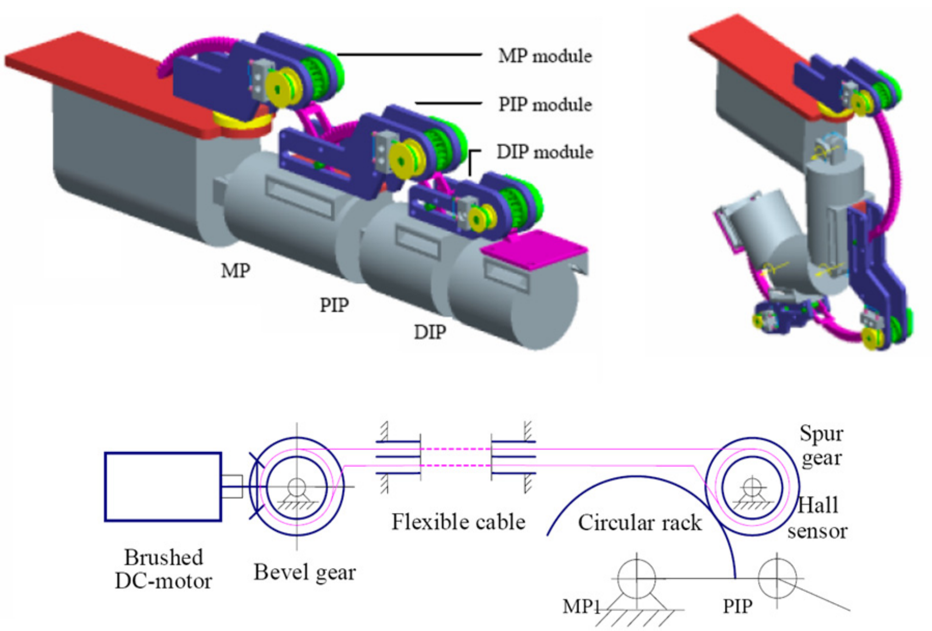


Fig. 11. CAD model and functional scheme for the flexion of the MCP joint of the Harbin Institute of Technology Hand (Taken from [6])

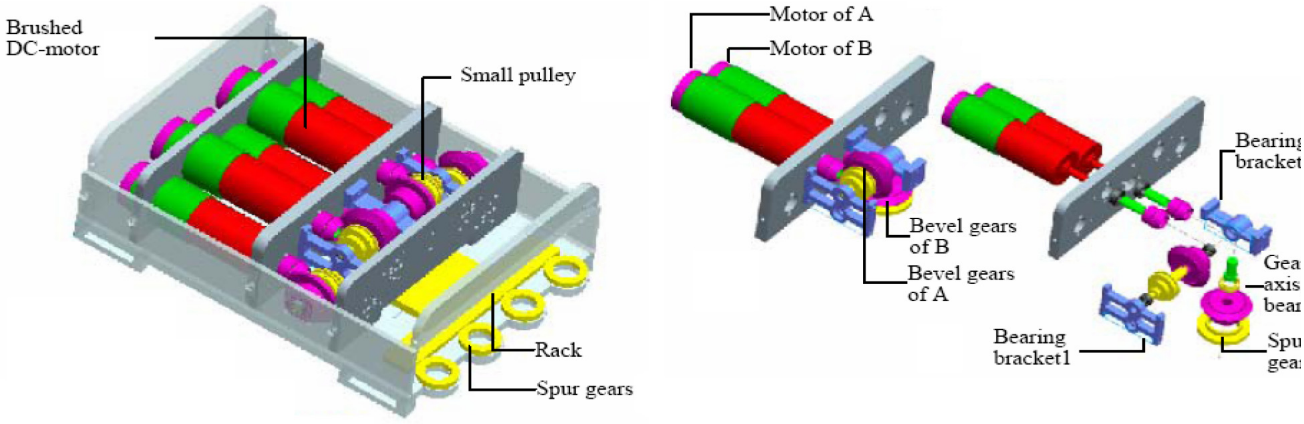


Fig. 12. Actuator units of the Harbin Institute of Technology Hand (Taken from [6])

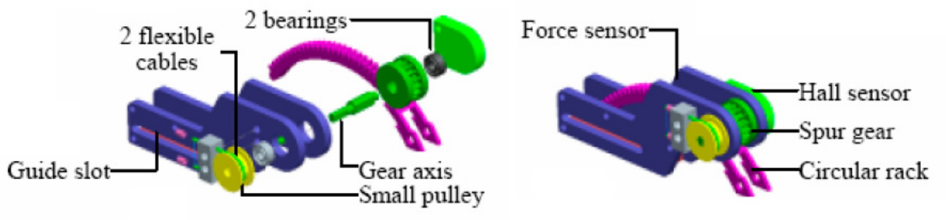


Fig. 13. Sensors mounted on the Harbin Institute of Technology Hand (Taken from [6])

The exoskeleton is equipped with position sensors (2 types) and force sensors. Two-axis Hall sensors are located on spur gears to measure joint angles in flexion. Another position sensor is a magneto resistant encoder embedded into the motor shaft, which is needed to provide feedback information about the rotation speed of the motor. The force sensors (internal force sensors) are the traditional strain gages which are located on each joints (Fig. 13). One end of the 6 wires is attached to the small pulleys which are placed on the force sensors, and the other end is attached to another small pulley which is moved by one DC motor
According to the authors, the most critical issue of this exoskeleton is the friction, that is mainly caused by the bevel gears, the circular rack and the spur gear, the flexible cable and the spring tube. The friction force in the system is always variable and high and negatively influences the system characteristics.

II.6 HWARD

The device was designed to support the rehabilitation process after hand injuries [7]. The exoskeleton is pneumatically actuated and supports repetitive power grasping and releasing movements of the human hand.

The device controls 2 DOFs of the human finger motion and 1 DOF of the wrist. The combination of 4 fingers is controlled with 1 motor for the flexion/extension about the MCP and PIP joints (Fig. 14). The device is attached to the combination of 4 fingers along the dorsal side of the fingers by a link. This link is fastened to middle phalanges of 4 fingers by looping a soft strap around the 4

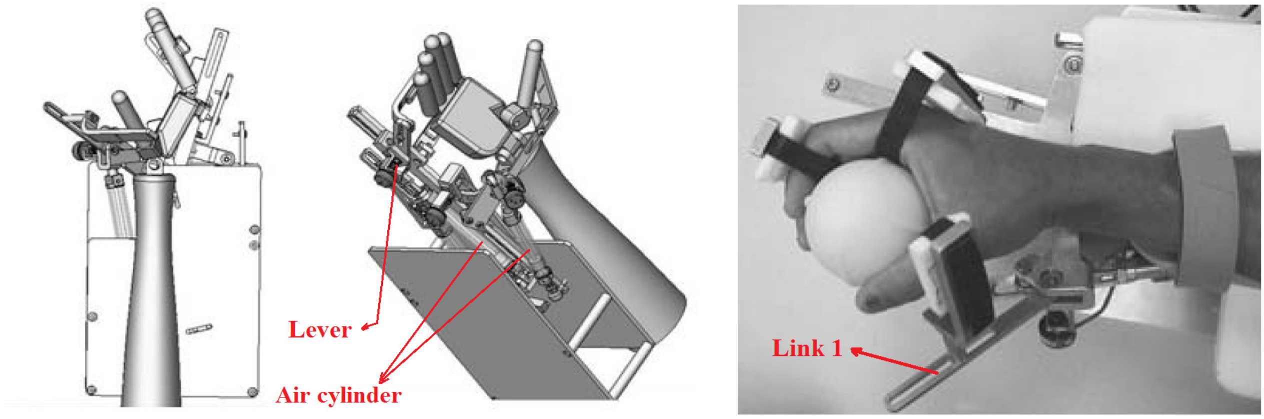


Fig. 14. HWARD (Taken from [7])

fingers. Movement of this link causes the movement of middle phalanges of combination of 4 fingers about the MCP and PIP joints. The movement of middle phalanges causes the movement of MCP and PIP joints. Although there is not any systematic mechanical coupling among MCP and PIP joints, the pose of middle phalanges causes certain situation of proximal phalanges, MCP and PIP joints. Distal phalanges and DIP joints of fingers are kept free.

Similarly to the group of the 4 fingers, the thumb is actuated with 1 motor for the flexion/extension about the CMC and MCP joints. The device is attached to the thumb along the dorsal side of it by a link (link 1). This link is fastened to the proximal phalange of thumb by a soft strap. Movement of this link causes the movement of the thumb about the CMC and MCP joints. Distal phalange and IP joint of the thumb are kept free.

Robot joint movement is achieved using a lever design. Each air cylinder and limb interface are mounted on opposite ends of the lever, with a revolute joint between them. Air pressure causes the movement of limb interface that causes the movement of levers connected to the human fingers. The system is actuated by 2 double-actuating air cylinders that can provide up to 122.8 [N] of force, but air pressure is regulated so that the air cylinders produce roughly 4-15 [N], the estimated level necessary to assist movement.

The system is equipped with 2 kinds of internal force sensors (pneumatic solenoid valve and micro structure pressure sensors) and position sensor (rotary potentiometers). The pressure of air injected into the cylinders is controlled by means of pneumatic solenoid valves and micro structure pressure sensors that are mounted on both sides of each air cylinder. The forces applied by the robot can be computed from data gained from these pressure sensors. In addition to pressure control, inline flow control valve adjust the rate of air injected to the cylinders. Rotary potentiometers measure the fingers, wrist and thumb joint angles. The control procedure is only based on position controlling and the main focus is on rehabilitation of power grasping.

II.7 Gentle/G Hand

This hand rehabilitation system is suitable for patients who are suffering from neurological problems [8]. The exoskeleton controls the movements of human fingers by applying force on the thumb and on the combination of 4 fingers (similarly to HWARD, just described).

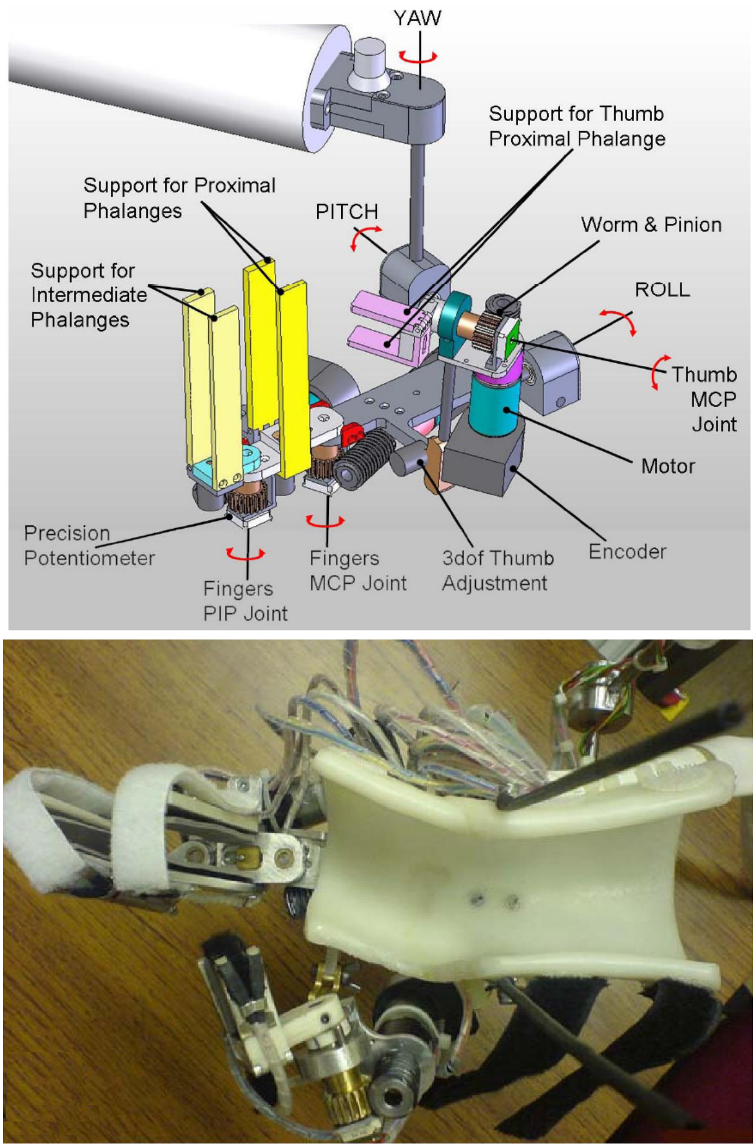


Fig. 15. The Gentle/G Hand exoskeleton (Taken from [8])

Gentle/G hand exoskeleton controls 3 DOFs of the human hand motion passively at the wrist level (roll, pitch and yaw) and 3 DOFs of the human fingers motion actively. The index, middle, ring and little finger are combined and actuated simultaneously with 2 DOFs (flexion/extension of MCP and PIP joints), whereas the distal phalanges and DIP joints of fingers are kept free. The thumb is controlled with 1 DOF (flexion/extension of MCP and CMC joints) and the distal phalange and IP joint of the thumb are kept free. as shown in Fig. 15.
The device is attached to the human fingers and thumb along 2 parallel support bars and Velcro straps are used to secure the parts in position. The power is transmitted to the robot joints by means of worm and pinion drive configuration. The power transmission chain of the mechanism consists of only motors plus worms and pinions that are directly placed along the axes of the actuated joints. The actuator part consists of DC motors with maximum power of 6 [W].
The exoskeleton is equipped with 2 different kinds of position sensors namely optical encoder and precision potentiometer and external force sensors. Optical encoders are installed into the DC motors to measure the angular position of the shaft, whereas the precision potentiometers directly

measure the joint angles. The potentiometers are used initially for resetting the encoders to their absolute value, and to monitor encoder/actuator failure. Force sensing resistors are integrated into the parallel bars of the phalange supports to measure the patient's force input in order to drive the motors using admittance control.

This HE was conceived rehabilitation processes in real environment and virtual reality as well.

II.8. Milan University Hand

The device was designed with focus on support of the rehabilitation process for people who have partially lost the ability to control correctly the hand musculature, for example after stroke [9]. The control method exploits EMG signals to control the movement of fingers.

This HE controls 2 DOFs of the human hand motion. The thumb is controlled with 1 DOF and the combination of 4 fingers is controlled with 1 DOF. The flexion movements of the thumb and of the combination of 4 fingers are actuated with 2 servomotors and wire-driven mechanism. Two wires are connected to the fingertips of the thumb and combination of 4 fingers and rolled up to the pulleys of the servos on the other end for actuating flexion movement. Actuating extension movement of fingers is done by use of 2 springs that are located on the dorsal side of hand and connected to the fingertips of the thumb and combination of 4 fingers as presented in Fig. 16. There is not any systematic mechanical coupling among MCP, PIP and DIP joints. So, because of internal DOFs among human joints, the movement of fingertip causes the movement of phalanges and MCP, PIP and DIP joints as shown in Fig. 17. Therefore, also this system consist of (two) under-actuated mechanisms.

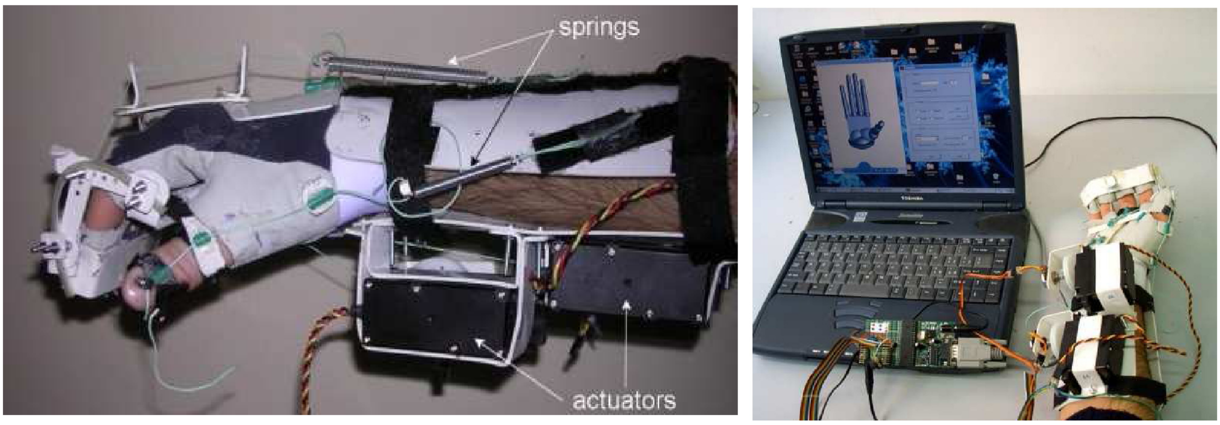


Fig.16. Hand exoskeletons from the University of Milan (Taken from [9])

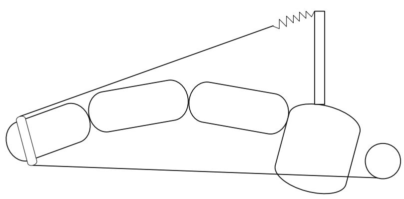


Fig. 17. Scheme of the under-actuated finger exoskeleton

The system is equipped with EMG electrodes to measure the electric activity of the muscles. By using these measured EMG signals, the system predict the intention to perform a certain movement and acts on the patient's hand in order to perform the task. Two potentiometers are placed on the pulley of the servomotors to measure the rotational angle of the links.

II.9. Pittsburgh University Hand

The device was designed with focus on the rehabilitation of natural pinching [10, 35]. The control method exploits EMG signals to control the movement of the index finger.
This exoskeleton controls 2 DOFs of the human index motion. The flexion/extension movement of PIP and DIP are coupled and actuated by means of a pneumatic piston and the flexion/extension movement of MCP joint is actuated by another pneumatic piston. The index finger has another passive DOF for the abduction/adduction movement. Pinching motion is performed by means of flexion of index finger against a fixed thumb (Fig. 18). The frame of the exoskeleton consists of an aluminum anchoring plate mounted to the back of the hand and three aluminum bands, one for each phalanx. The flexion of the PIP and DIP joints is produced by a steel cable running along the front of each finger band and through to the backside of the hand. This cable is pulled by a pneumatic cylinder acting in compression. The extension movement of the PIP and DIP joints are produced by 2 springs as shown in Fig. 18. The MCP flexion is achieved by a linkage mechanism: a floating link is mounted between the finger band closest to the base plate and a second pneumatic actuator. When this pneumatic piston pushes the link mechanism forward (distal), the MCP joint is flexed. The extension movement of the MCP joint is produced by a spring (Fig. 19). To achieve smooth repeatable motion and the passive abduction/adduction motion, the flexible coupling added between the base-plate and first finger band is made of a canvas-like cloth material.
The exoskeleton movements are controlled by the users biceps EMG signals. The pistons are equipped with variable pressure pneumatic valves to control the maximum forces exerted to the finger phalanges.
The system is mainly focus on repeatedly movement of index finger in pinching. The system is not equipped with any position sensors. So, there is not any control on position of the finger joints.

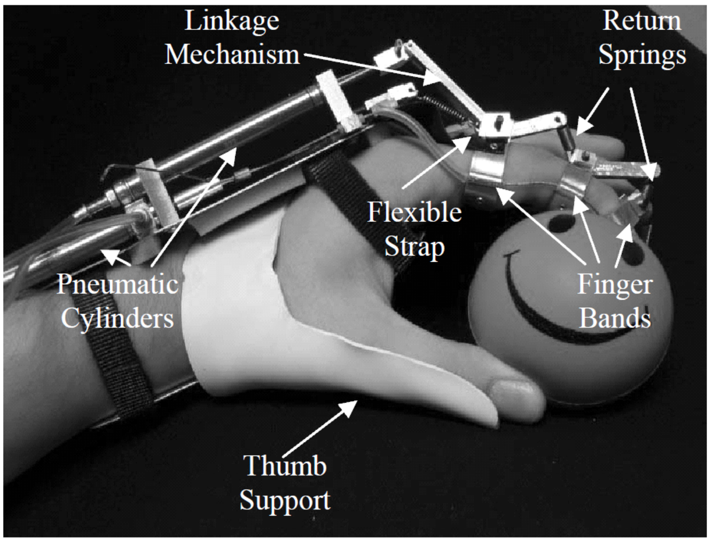


Fig. 18. Pittsburgh University Hand exoskeleton (Taken from [35])

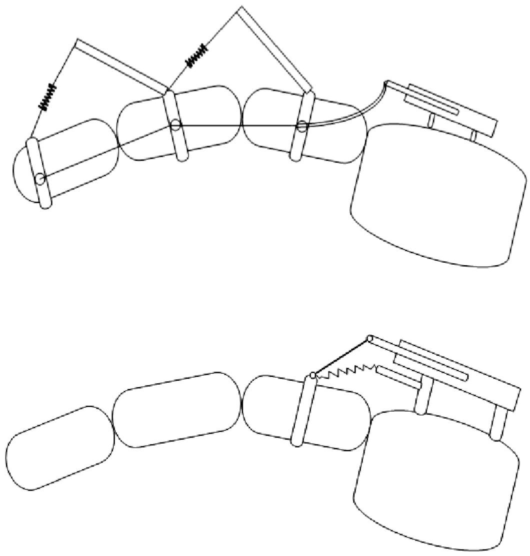


Fig. 19. Schematic model of the Pittsburgh University Hand

II.10. HANDEXOS

The device was designed with the purpose of supporting the rehabilitation process after stroke [11]. The exoskeleton uses an under-actuated mechanism that enables the hand to passively adapt each finger to the generic shape of the grasped object (self-adaptation).

The 5 fingers HE controls 5 DOFs movement of the human hand. Each finger is supported by 1 DOF: the flexion/extension of DIP, PIP and MCP joints are actuated by means of a single DC motor and the abduction/adduction movement of MCP is supported passively (Fig. 20).

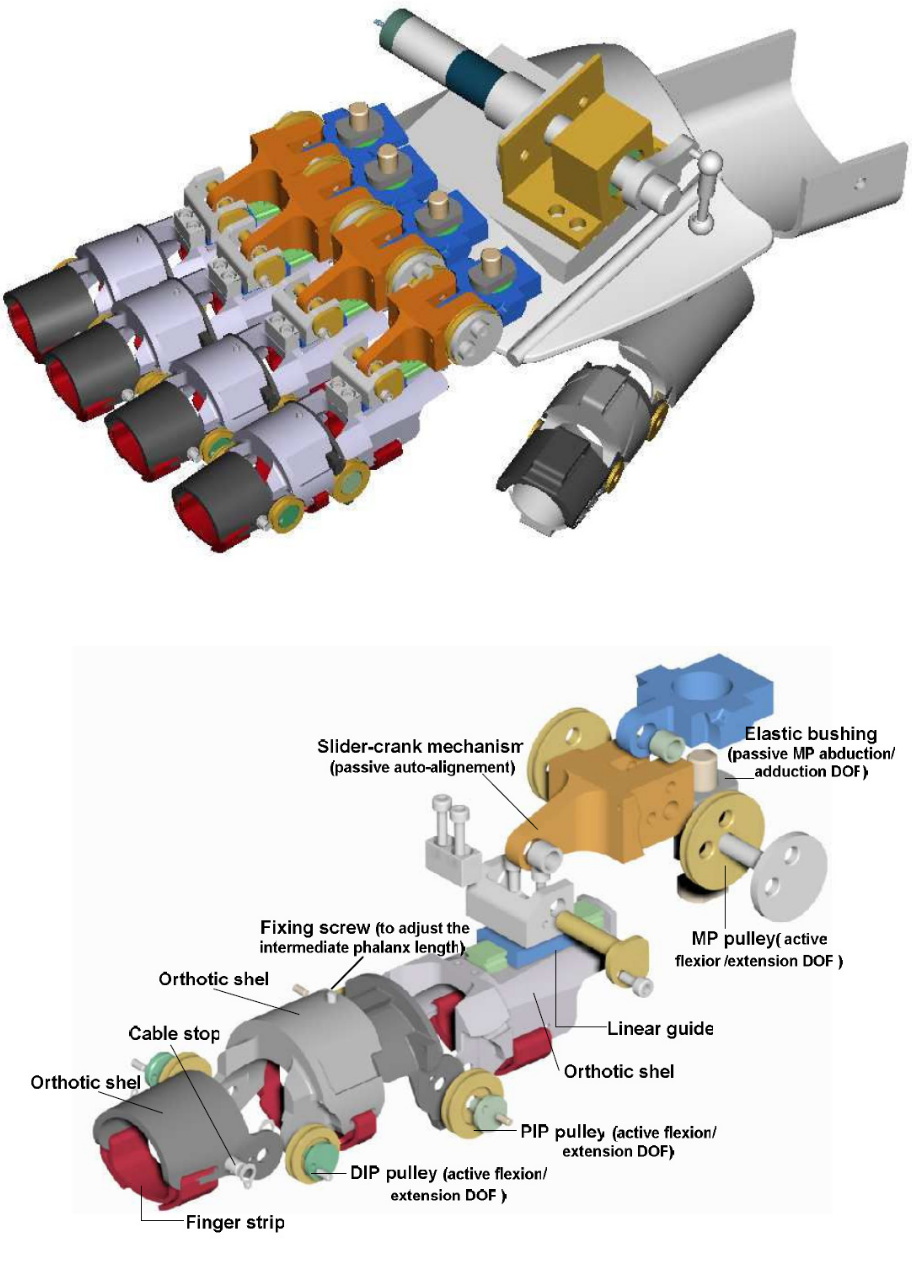


Fig. 20. HANDEXOS concept (Taken from [11])

This HE exploits 2 different strategies to make the exoskeleton joint axes coincide with those of the human finger. For DIP and PIP joints, 4 pulleys, 2 for each joints (one for actuating the flexion and one for extension), are placed on both sides of Handexos finger at the level of the wearer's finger joint (Fig. 21). For the MCP joint, 2 pulleys are placed above the human MCP joint to actuate

flexion/extension movement of finger. These pulleys are connected to the first phalanx by a passive prismatic joint (Fig. 22). By using this slider-crack mechanism, the length of the link could be adjusted passively to avoid interference between exoskeleton and human finger during the flexion movement of MCP joint.

The actuator unit consists of 1 DC motor that is used to extend the coupled DIP, PIP and MCP joints, as shown in Fig.23. The extension movement of each finger is actuated by a cable running across idle pulley placed in each finger joints and fixed to the distal phalanx through a cable stop. The cable is pulled through a linear slider by a DC motor placed extrinsically.

The flexion movement of the finger is passively obtained by means of a set of three (one for each joint) antagonist cables running across the pulleys placed on the other side of the finger, connected to three extrinsic linear compression springs whose elastic torques cause the finger to flex (Fig. 24).

The main advantages of the under-actuated mechanism that is used in this HE is its capability of self-adaptation. Indeed, the finger is enabled to passively adapt each finger to the shape of the grasped object (it is worth recalling that the flexion movement is provided by the elastic force of springs).

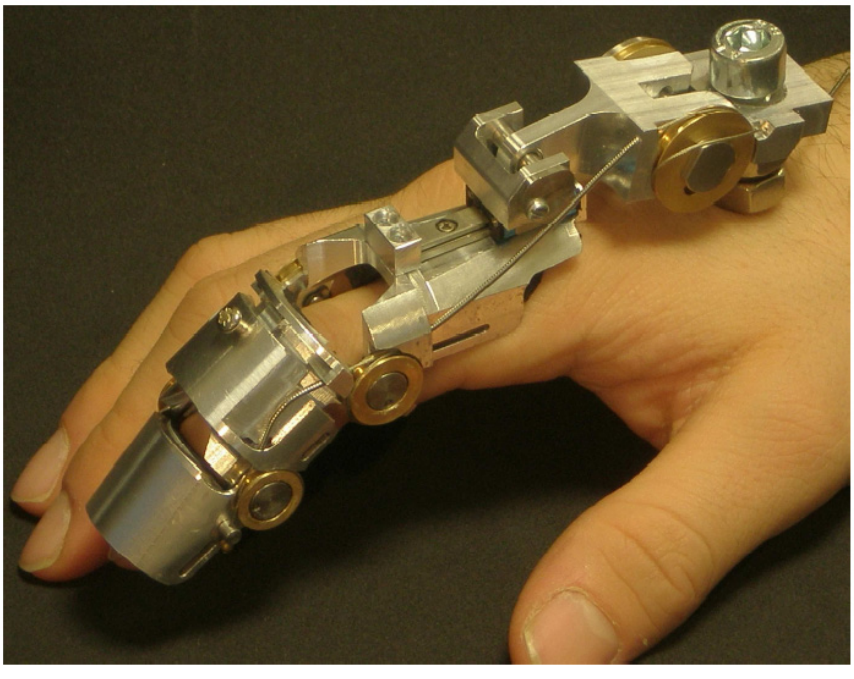


Fig. 21. HANDEXOS finger mechanism (Taken from [11])

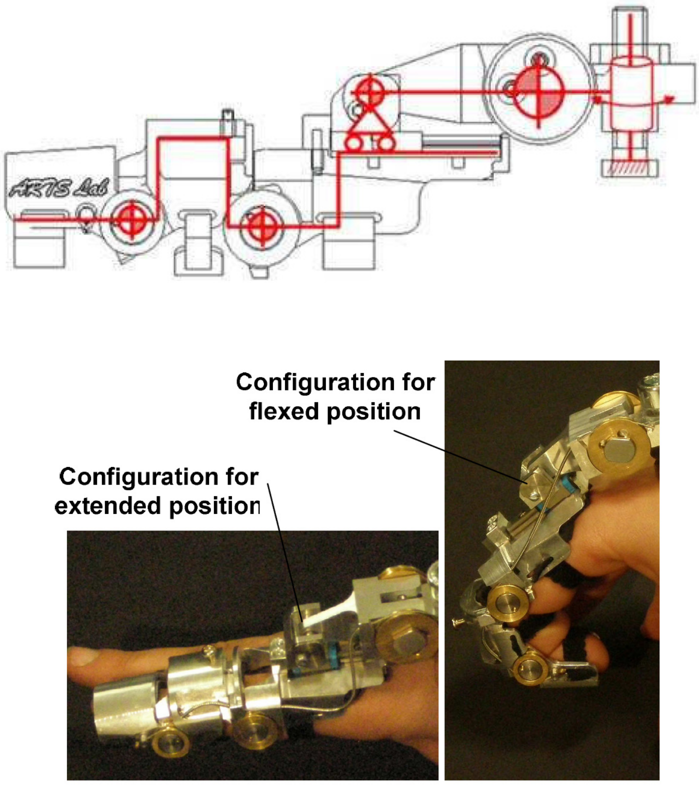


Fig. 22. Slider-crack mechanism for MCP joint of HANDEXOS (Taken from [11])

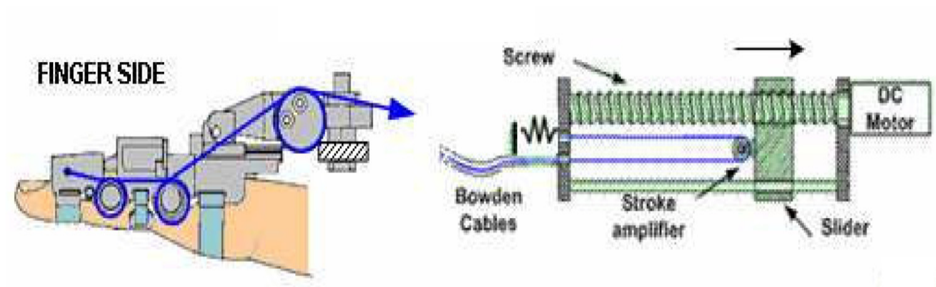


Fig. 23. Scheme for the extension system of HANDEXOS (Taken from [11])

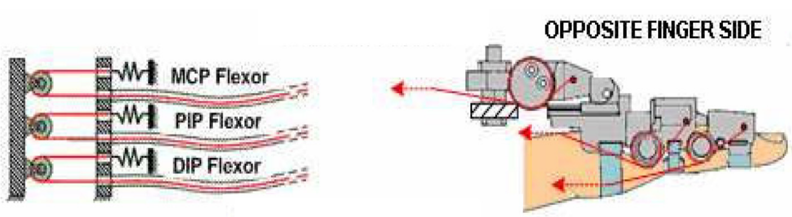


Fig. 24. Scheme for the flexion system of HANDEXOS (Taken from [11])

II.11. Beihang University Hand

The device was designed to support the rehabilitation of the index finger [12].

This HE controls 4 DOFs of the human index motion. The exoskeleton actuates the finger flexion/extension by means of 3 closed chain mechanisms. Each 1 DOF chain mechanism consists of 2 human finger phalanges and 2 external links, connected through 2 external prismatic joints, 1 external revolute joint, 1 human finger joint (Fig. 25). A sector wheel is fixed to the distal external link and is coupled with the proximal one by means of the external revolute joint. The rotation of this sector wheel causes the rotation of the distal link. According to the configuration, the length of the link is adjusted automatically by the slider in order to avoid mechanical interference between human finger and HE(Fig. 26).

A cable transmission system is used to actuate each joint. Two wires are used to transmit the force from the driving wheel to the sector wheel. Each driver wheel is connected to the DC motor, so that 4 DC motors are required for the index finger. With reference to Fig. 27, when the driving wheel rotates in one direction, the cable 1 is pulled to drive the sector wheel to realize finger flexion, while the opposite direction can achieve finger extension by pulling the cable 2. Driving wheel is connected to the speed reducing wheel and the rotation of reducing wheel causes the rotation of driving wheel. The speed reducing wheel is connected to the threaded spindle by use of 2 wires and the threaded spindle is directly actuated by the DC motor.

The angular position of the joints is calculated by rotary encoders installed into the DC motors. Additionally, the system is equipped with 2 external force sensors in each phalanx to measure the force exerted by the exoskeleton to the human fingers.

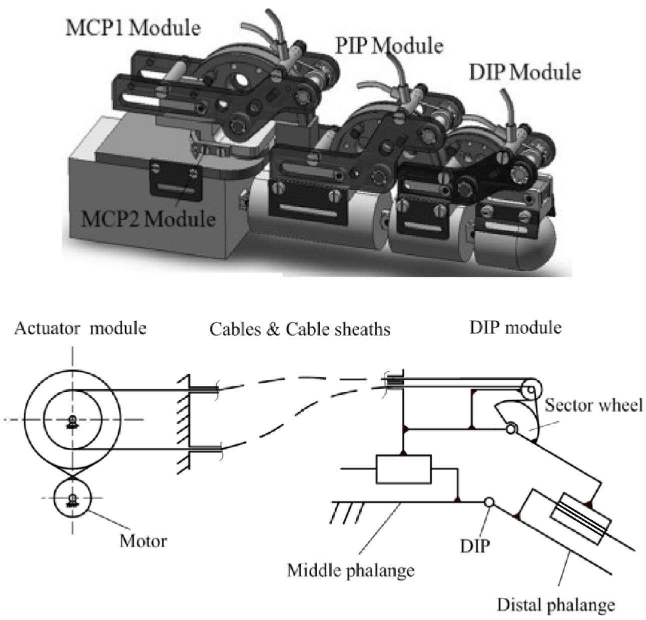


Fig.25. Layout of the Beihang University Hand
(Taken from [12])

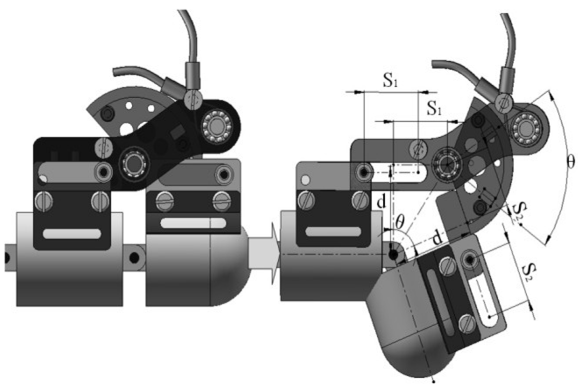


Fig. 26. Bending of a finger joint
(Taken from [12])

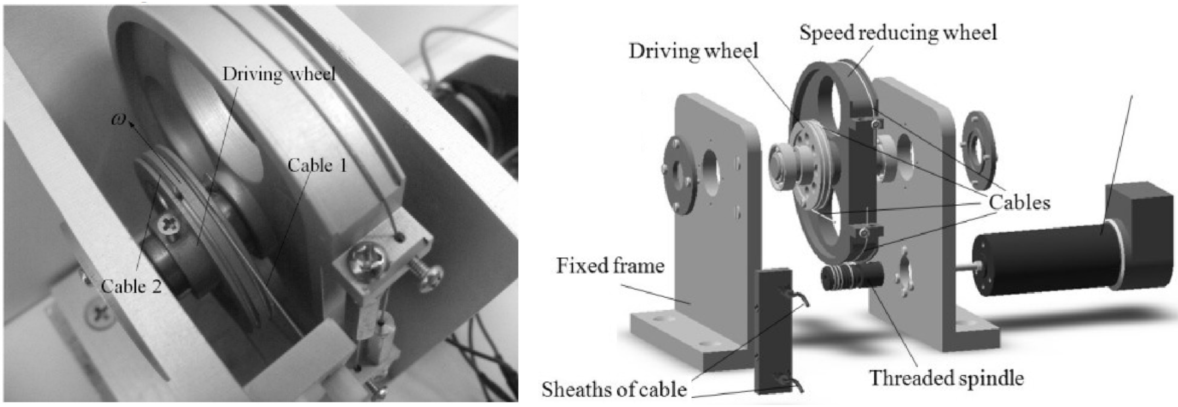


Fig. 27. Actuator module of the Beihang University Hand (Taken from [12])

II.12 Sabancı University Hand

This finger exoskeleton is a rehabilitation device that is specifically designed for the tendon repair therapy exercises [13].

This exoskeleton controls 1 DOF of the human index motion. The mechanism is attached to all finger phalanges (proximal, middle and distal). The flexion/extension of DIP, PIP and MCP joints are actuated by means of a single DC motor (Fig. 28). Figure 29 depicts a schematic representation of the kinematic structure used for the exoskeleton and presents motion of the device against an obstacle. The kinematics of the exoskeleton is effectively equivalent to the kinematics of a series of five-bar mechanism (links: 1, 2, 3, 4, 5) and a four-bar mechanism (links: 4, 6, 7, 8) that are coupled to each other with 2 compliant springs and constrained by mechanical joints limits. The springs maintain the second and third phalanxes of the finger in fully extended configurations until the first phalanx comes in contact with an obstacle or reaches a mechanical limit. When the mechanism is free of contacts and within joint limits, it behaves like a single rigid body. But when the motion of a phalanx is resisted, the torque generated by the motor overcomes the spring pre-load and the adjacent phalanx initiates motion. The motion continues sequentially until motion of all phalanxes are resisted due to either contact with the object or a joint limit is encountered.

This HE exploits 2 different strategies to make the exoskeleton joint axes coincide with those of the human finger. For DIP and PIP joints, the device joints (DIP and PIP pulleys) are placed beside the wearer's finger joint (Fig. 28). For the MCP joint, the exoskeleton uses a five-bar mechanism. It contains 3 external links (2, 3, 4) and 2 human finger links [1, 5 (human proximal phalanx)]. Furthermore, it contains 4 external joints and 1 human joint (MCP), as schematically represented in Fig 29.

The system is equipped with 2 different kinds of position sensors: potentiometers and encoder. Two potentiometers are instrumented at the joints coinciding with human PIP and DIP joints. Additionally, an optical encoder is used to measure the position of the motor axis. Three external force sensors are placed between the human finger attachments and the exoskeleton. The control system is equipped with EMG electrodes to sample muscles activity and to evaluate the power-assist performance.

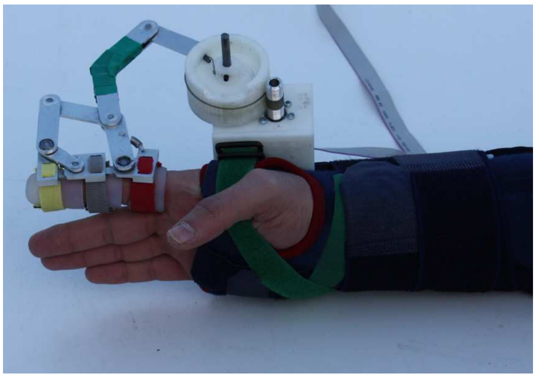


Fig.28. Hand exoskeletons from the Sabanci University (Taken from [13])

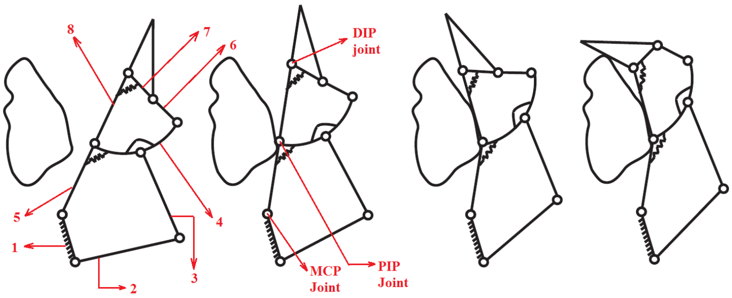


Fig.29. Schematic model of the Sabanci University Hand (Taken from [13])

II.13. SKK Hand Master

This is a haptic machine named "SKK Hand Master" [14, 36]. The hand adopts four-bar linkage mechanisms directly driven by means of ultrasonic motors (without speed reduction stages)

SKK Hand Master is a 2 finger hand with 4 DOFs in index finger and 3 DOFs in thumb (Fig. 30). The exoskeleton assists finger movement by means of 3 four-bar mechanisms. Each four-bar mechanism is directly actuated by a light-weight ultrasonic motor (Fig. 31).

The device is equipped with 2 kind of sensors namely force sensor and angular position sensor. The haptic device measures the position of user' finger by means of position sensors that are located on external links in each four-bar mechanism. The force presented to the user's finger is measured by external force sensors that are placed in each four-bar mechanism. The data received from these sensors are used in virtual reality applications or to control the finger position of a remote grasping

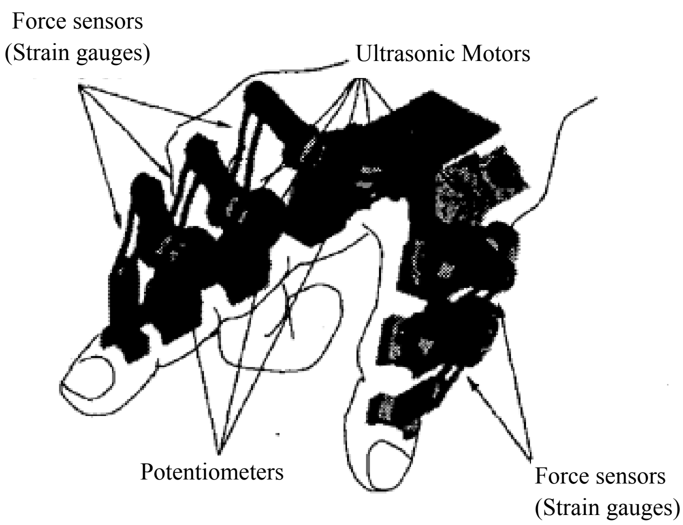


Fig. 30: SKK Hand Master (Taken from [36])

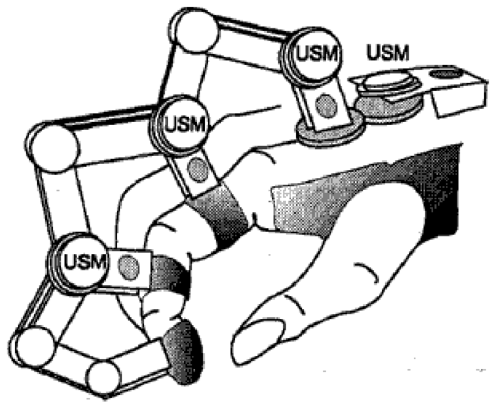


Fig. 31: Conceptual design of exoskeleton type hand master index finger. (Taken from [14])

manipulator. The force feedback that is presented to the user's fingers helps to feel deeper human sensation of touch and force.

Ultrasonic motors have several advantages over typical electrical motors: light weight, silent motion and high power-to-weight ratio. On the contrary, they have some drawbacks such as hysteresis and temperature rise in case of long term operation as well as a pretty high cost.

II.14. PERCRO Hand I

The main target of this 2 finger HE is the haptic interaction in virtual environment or in tele-manipulation system [15, 37]. The exoskeleton interacts with the human hand by exerting force on the fingertip of the index and thumb of the user.

This 2 finger haptic device is a hand with 3 DOFs in index finger (with coupled DIP and PIP joints) and 3 DOFs for thumb as presented in Fig. 32.

A crucial aspect must be explained in the architecture of these kind of exoskeleton, which is placed over an operator finger. To mimic the motion of the operator, the rotation centers of the exoskeleton machine should coincide with the rotation centers of the operator fingers to avoid mechanical interference (Fig. 33). Through avoiding this interference, many kinds of Remote Center of Motions mechanisms (RCMs) can be used. RCMs are mechanisms that are able to implement the rotation of a body around a fixed axis that is remotely located from the structure of the joint. A six-bar mechanism, which is composed of two connected parallelograms, is one kind of RCM that is used in this hand. Because of these parallelograms, the instant center rotation is fixed relative to the fingers (Fig. 34).

Further, the coupling between DIP and PIP joints has been implemented through a crossed parallelogram mechanism as shown in Fig. 35.

The actuator part for each finger contains 3 electrical motors, and force transmission is done by means of a wire-driven mechanism. A novel method for actuating the RCM has been introduced in this HE because the simple use of capstan-pulley system is not useful in this exoskeleton (Fig.36 a). The main drawback of this solution is that the radius of the driven pulley has to be very large in

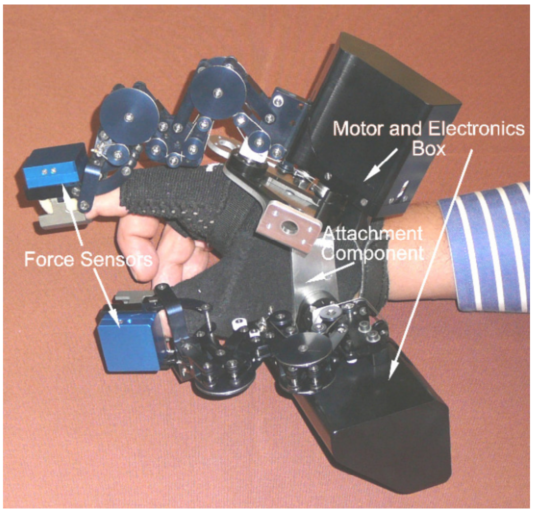


Fig. 32. PERCRO Hand I (Taken from [15])

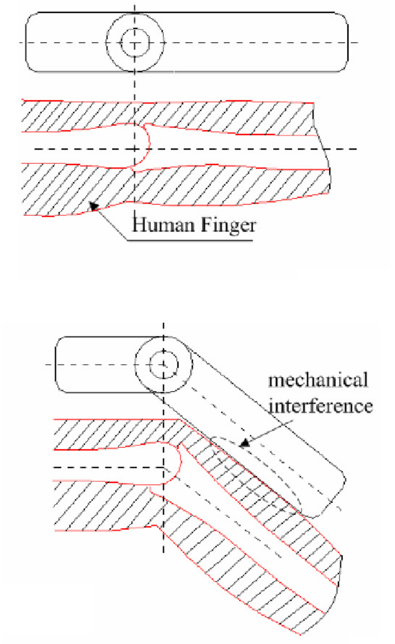


Fig. 33. Interference between the machine and the human finger (Taken from [17])

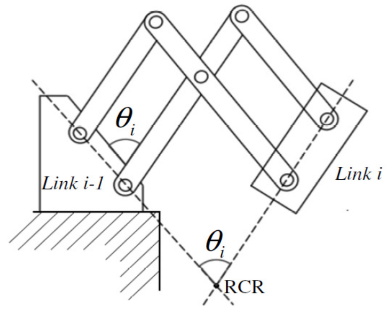


Fig. 34: Scheme of the Remote Center of Motion (Taken from [15])

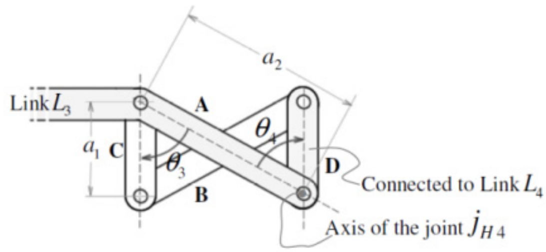
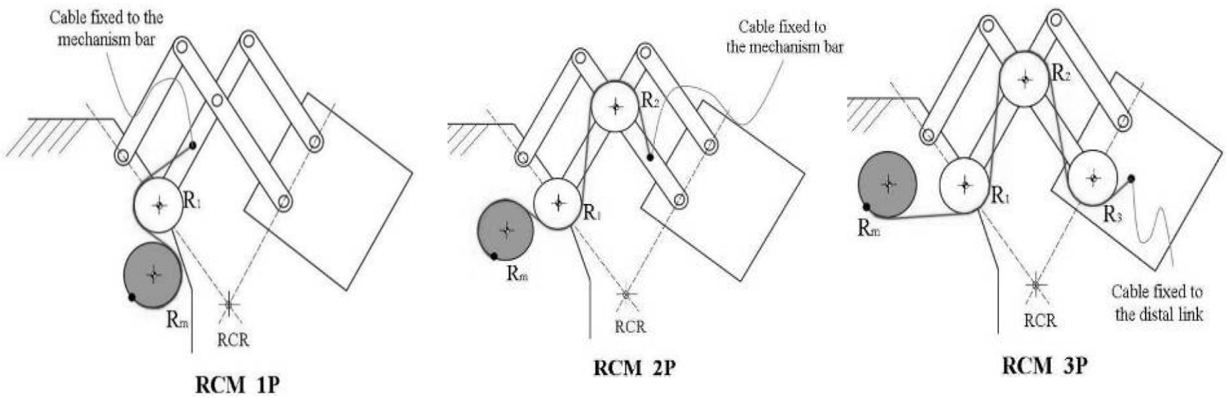


Fig. 35. Coupling mechanism for DIP and PIP joints (Taken from [15])

order to reach a consistent speed reduction ratio. The idea for solving the problem was to exploit the mutual rotation of the various links of the RCM structures in order to multiply the length change of the cable when the mechanism rotates (Fig 36 b and c). The implementation of this idea is achieved by adding multiple idle pulleys coaxial with the rotation axes of the RCM and arranging the cables path beginning from the motor pulley, wrapping around the different idle pulleys and ending on attachment point on a link.



(a) (b) (c)

Fig. 36. Different solutions for the power transmission with a RCM mechanism (Taken from [15])

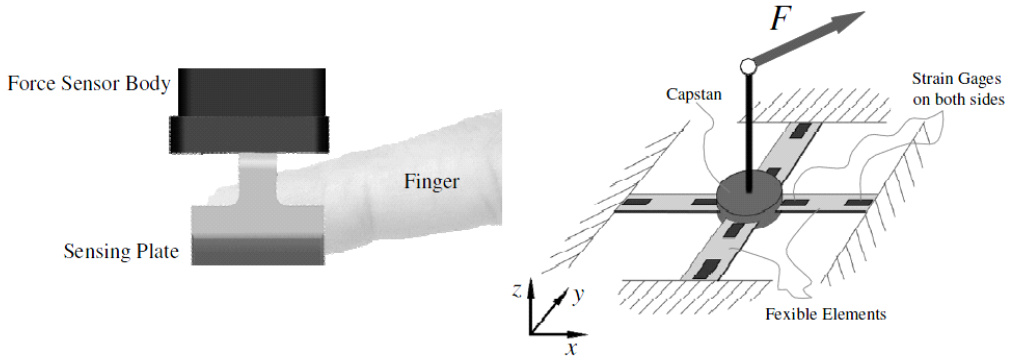


Fig. 37. Force sensor used in PERCRO Hand I (Taken from [37])

The system is equipped with a bi-directional force sensors on fingertip of thumb and index finger (Fig. 37). In addition, the motors' current draining is measured to compute the torque at the motor axes. The position of the links is measured by means of encoders, whose data make it possible to implement a position control strategy of fingers modeled in virtual reality applications.

The device is able to exert a force of 5 N on each fingertip with a global weight of 1.1 kg. A smart solution for the cable transmission improve the global weight stiffness of the device through the realization of intrinsic speed reduction ratio.

II.15. PERCRO Hand II

The main target of this 2 finger HE is the haptic interaction in virtual environment [16]. The exoskeleton, which is characterized by a large workspace, controls the movement of human hand by exerting force on the fingertip of the index and thumb of the user.

This 2 fingers haptic device is a hand with 3 active DOFs in index finger and 3 active DOFs for thumb as presented in Fig. 38. Differently from other solutions, this system has a non-anthropomorphic structure: indeed the mechanism for each finger can be considered as a 3-DOFs serial manipulator conceived for positioning its terminal device (attached to the human fingertip in order to drag this last) in the Cartesian space.

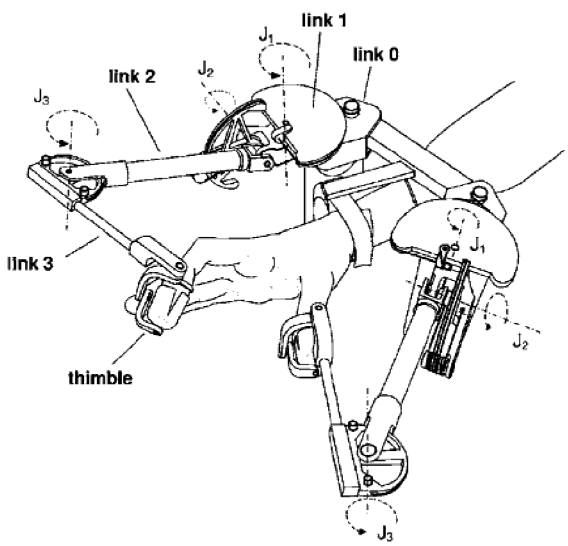


Fig. 38. A scheme of the PERCRO Hand II (Taken from [16])

The exoskeleton is composed of 2 serial connected links called “finger mechanisms” that are attached to the link 0. The link 0 is fixed to the forearm. Each finger mechanism has 4 links and 3 active DOFs. A thimble is coupled with a spherical passive joint to the end of each finger mechanism in order to connect the mechanism to the human finger with any possible relative orientation. All the kinematic pairs are implemented through rotational joints and the actuation of them is implemented by means of wire driven mechanism. All motors are located on link "0".

This 2 finger mechanism exoskeleton can track any movement of the thumb and index fingertip, including hand rotation generated by the wrist.

II.16. DLR/HIT Hand

This is a master hand with focus on bidirectional force feedback and natural touch sensation [17, 38]. The exoskeleton adopts optical sensor in order to define contact and non-contact mode on operator's fingertip.

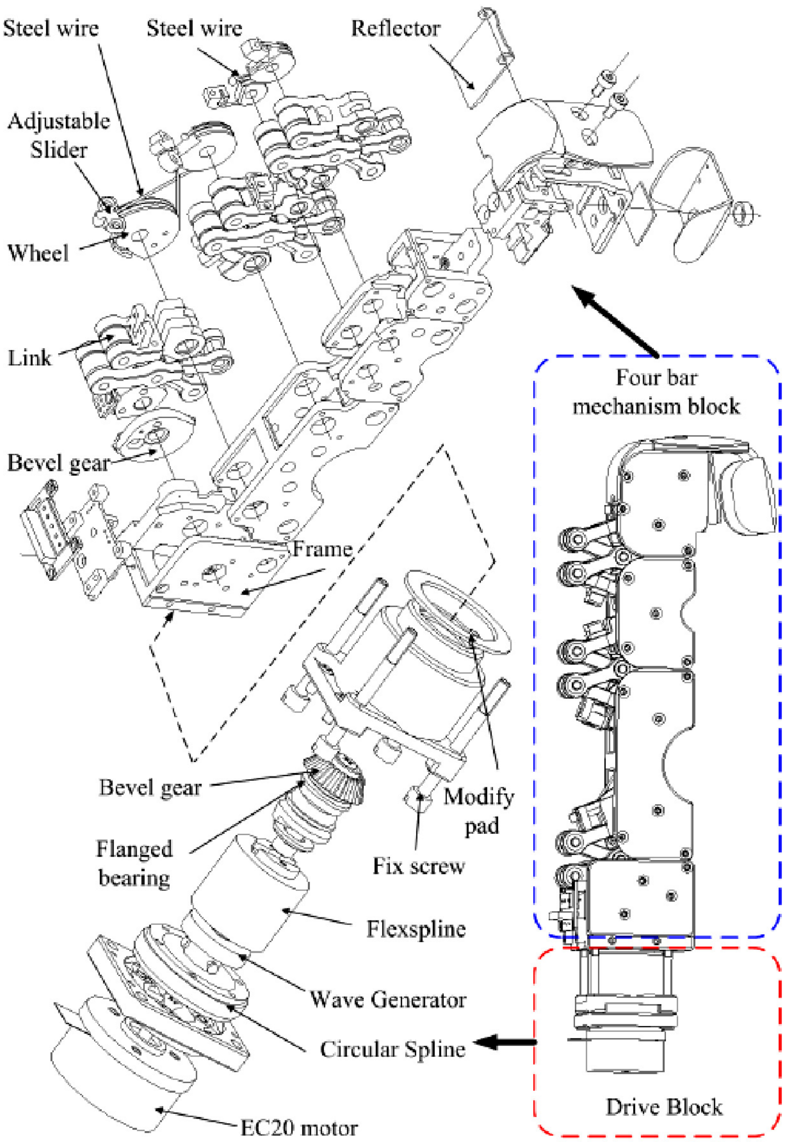
DLR/HIT master hand is made up of 5 fingers with 1 DOF in each finger. There are 3 coupled six-bar mechanism in each finger which mimics flexion/extension of PIP, DIP and MCP joints (as shown in Fig 39).

The drive block for each finger is made up of brushless motor, mini harmonic drive and bevel gears (reduce rate 2:1) which directly actuates the first six-bar mechanism (flexion/extension of MCP). The middle transmission between any two adjacent six-bar mechanisms employ steel wires and adjustable slider mechanism which makes it possible to keep the coupled transmission ratio 1:1.4 between MCP and PIP, and 1.4:1 between PIP and DIP, respectively.

Master hands are usually attached to the human finger by use of tapes. So, the movement of the human finger causes the movement of the master finger. When the controlled slave hand does not touch anything, the master hand works in passive mode, so the human finger and the master finger move together without exerting any force from master hand to the human finger. In reality, because of friction and stiffness between connections and mechanical links, the human finger senses a light force even if the slave hand does not get in contact with anything. In this HE, there is not any solid and rigid connection or tape between human hand and master hand, but a special sensor apparatus is used. When the slave hand touches nothing, the master hand follows the human finger without any contact, in what is called "non-contact mode". When the slave hand touches an object, the master fingers provide the operator's finger with resistive forces.. This situation is called "contact mode".

In order to distinguish contact and non-contact mode, the distance and the interaction force between the tip of the human finger and the tip of the master finger is measured. To this purpose an optical sensor and a reflecting plate with spring to detect the distance between human finger and master finger are used (Fig. 40). The spring is necessary to provide a tiny resisting force to the plate, so that the plate is always connected to the dorsal side of fingertip (nail).

In non-contact mode, when the operator move his/her finger, only position control is employed to keep the distance between human finger and master finger constant. In this mode, the operator hardly feel the force exerted from reflecting plate to his finger. When the slave hand touches an object (contact mode), the control procedure changes into force control and the master finger provides a force equal to the force applied to the slave finger.



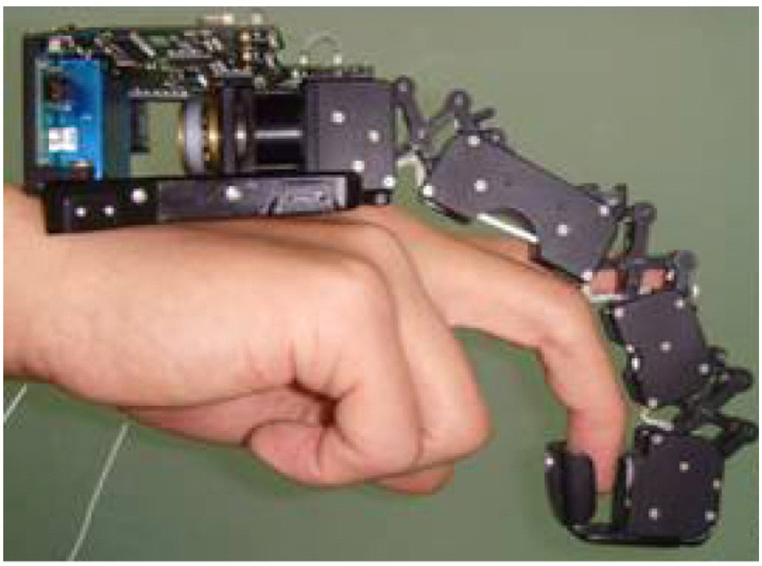


Fig. 39. DLR/HIT Master Hand (Taken from [17])

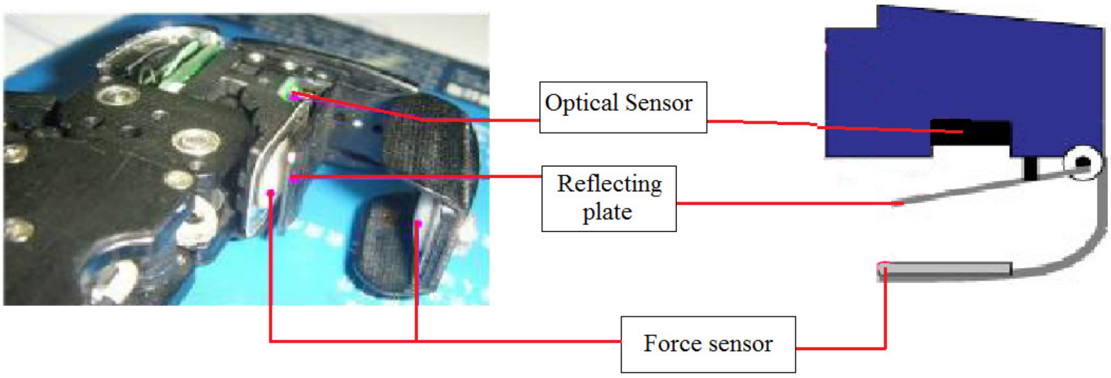


Fig. 40. Optical sensor, reflecting plate and force sensors used in DLR/HIT Master Hand (Taken from [17])

The system is equipped with 2 thin force sensors that are located at the upper and lower part of the tip of the master hand. In addition, in base joint, there is one strain gauge for calculating the motor torque and one non-contact hall sensor for detecting the angular displacement of the master finger.

The main advantages of this HE is the use of optical sensors for contact and non-contact mode. This makes it possible to touch nothing when the slave hand is in free space and when the slave touches an object the master hand switches from position control to force control.

II.17. University of Tokyo Hand II

This is a master hand to control dexterous robot [18]. The exoskeleton is equipped with a Circuitous Joint as a RCM mechanism. The exoskeleton uses optical sensors which supports contact and non-contact mode.

This exoskeleton controls 1 DOFs of the human finger. Through avoiding mechanical interference between the finger and exoskeleton in bending, this hand applies Circuitous Joints for DIP, PIP and MCP joints. Circuitous Joints solved the problem by extending the link length in proportion to the joint angular displacement. In order to do this, the mechanism exploits a rack and sectors gears (the presence of the rack makes this Circuitous Joint mechanism slightly different from that presented in III.4). A sector gear rotates on a rack by relative rotation of two links and movement of the gear center axis produces movement of the link as shown in Fig. 41.

A wire driven mechanism is applied to actuate the finger in direction of extension. To produce a force in the direction of flexion, a compression spring is used. Three Circuitous Joints are coupled and each rate of rotation is decided by the radius of the drum as shown in Fig. 42. Wires are driven by one motor and the maximum force applied on fingertip is about 8 [N].

Position control and force control are two control procedures that are used in this HE. A photo reflector and a reflecting plate are used in non-contact mode to guide the movement of exoskeleton in position control (according to the same conceptual scheme presented in III.15). Further, there is a thin force sensor placed at the tip of master hand to measure the force through force control in contact mode. Motor torque and motor angular displacement are measured and controlled at the base points.

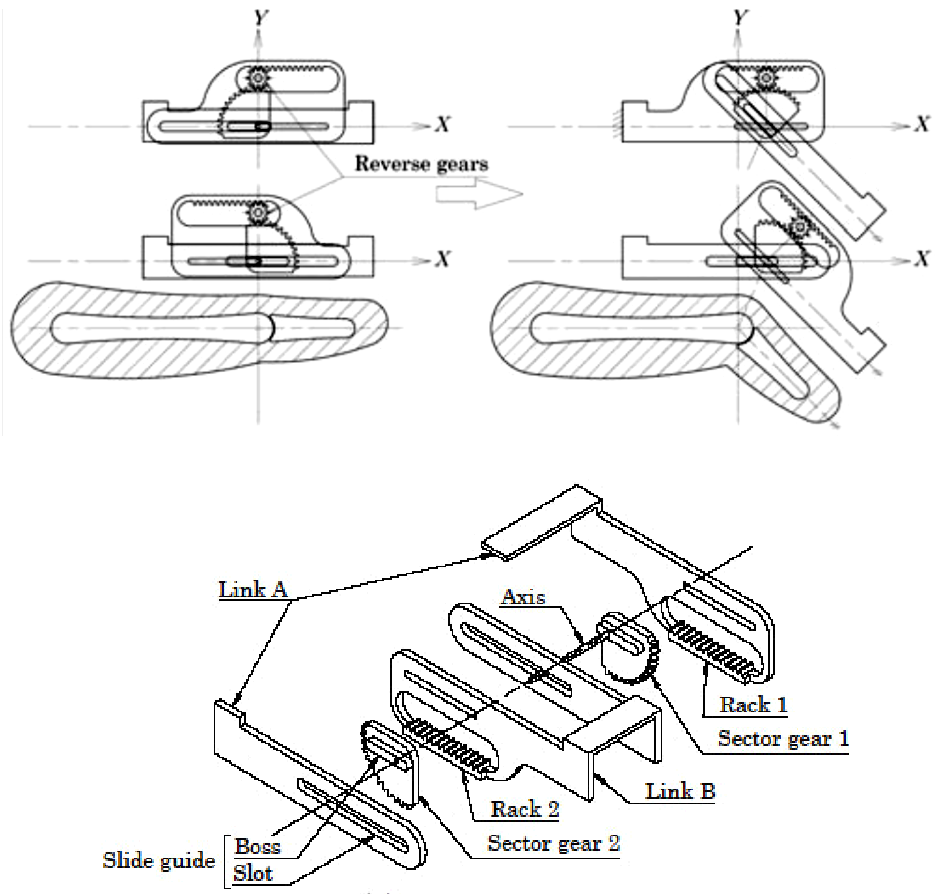


Fig. 41 The Circuitous Joint with upper side racks and reverse gears used in University of Tokyo Hand II (Taken from [18])

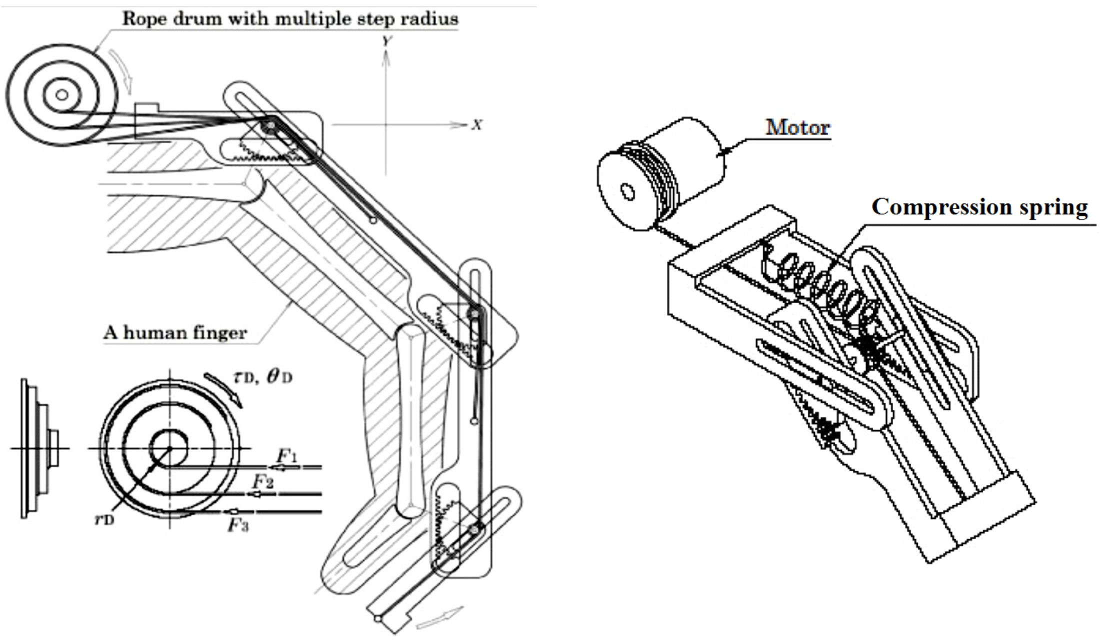


Fig. 42 a) Coupled driving method of the master finger
b) actuation scheme of the finger joints in the direction of flexion (Taken from [18])

This hand uses a special kind of mechanism (i.e. the Cicuitous Joints) to make the rotation of the master finger and that of the operator coincide in all rotation angles. There are some critical points here. The relation between the rotation angular displacement and the extension stroke of the link must be nonlinear to completely coincide with the human joint center. This means that the rectilinear rack and the sector gear whose radious is constant are not appropriate because the relation between the rotation angular displacement and the extension of the link is linear. However, it is possible to keep the error in acceptable range by minimizing the value of errors between ideal and real positions of the master hand's fingertip.

II.18. Robotics Center-Ecole des Mines de Paris Hand

This is a haptic device with focus on the bidirectional force feedback for virtual reality applications [19].

The haptic interface is a 2 finger hand with 1 DOF in the index finger and 1 DOF in the thumb. The flexion/extension movement of PIP, DIP and MCP joints of index finger are coupled and controlled with a planner motion by use of a 4-link serial mechanism. This serial manipulator is connected to the fingertip of the human finger, thus forming a closed chain (Fig. 43) having 3 DOFs (if considered a planar mechanism). The authors chose provide this system with 1 actuator only (resulting in an under-actuated mechanism) in order to limit the machine weight.

The 4 DOFs of the human thumb are coupled and actuated by only 1 motor by using two pulleys of the same radius. With reference to Fig. 44, when the thumb rotates (adduction), as one part of the cable wraps around the first pulley and the dotted part unwraps around the second pulley for the same degrees, the total length of the cable remains constant. According to this solution, the adduction and the flexion of the thumb are coupled.

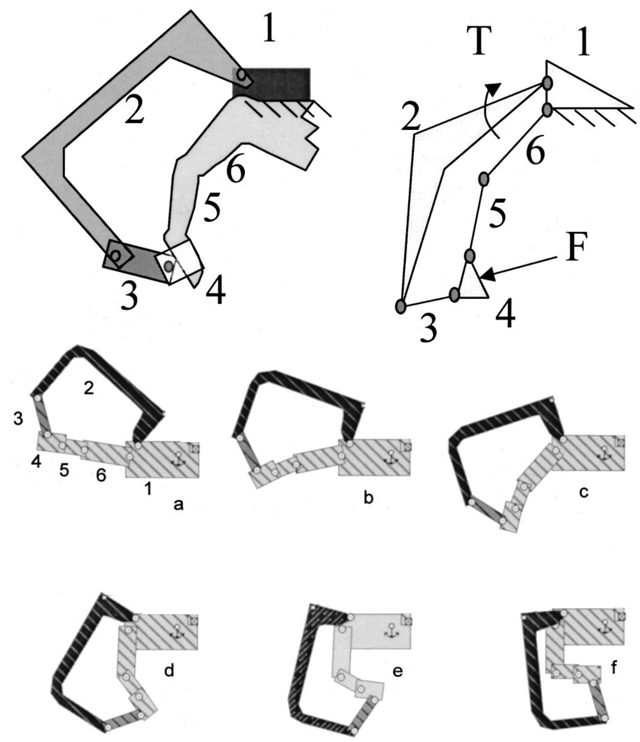
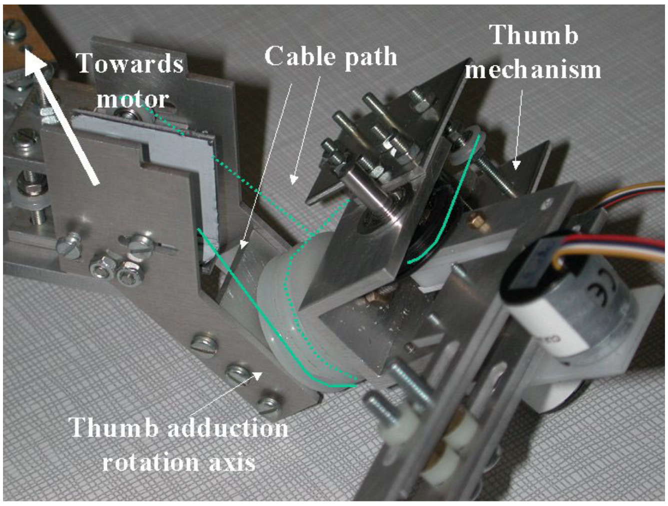


Fig. 43. Six bar linkage formed when the operator wears the haptic mechanism (Taken from [39])



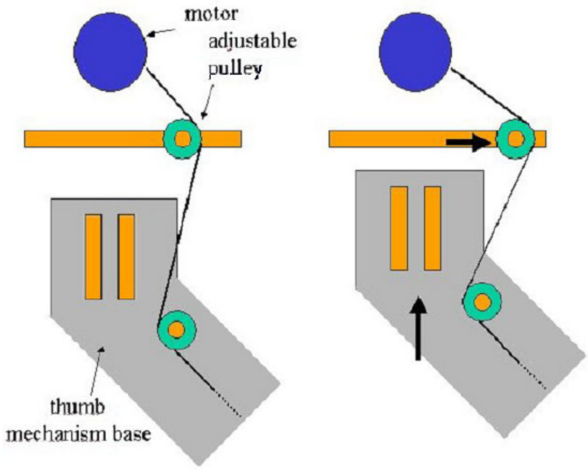


Fig. 44. Cable paths around thumb (Taken from [19])

Fig. 45. Cable length adjustment for moving the thumb base (Taken from [19])

Through adjusting thumb for different hand size, the length of the cable should change. For overcoming this problem, intermediate pulleys whose axis can translate has been used (Fig. 45).

The control procedure is based on position controlling. The device is equipped with 5 encoders which measure the angular displacement of links. Two encoders are used in index finger, 1 in motor and another in first actuated joint. Three encoders are used in thumb, in particular 1 embedded into the motor and 2 other ones are placed on pulleys for measuring the abduction/adduction and flexion/extension of the joints as shown in Fig.46.

The system does not use any force sensor to measure the fore exerted to the hand. It could be dangerous in some cases, due to the possible uncontrolled forces transmitted to the user's hand.

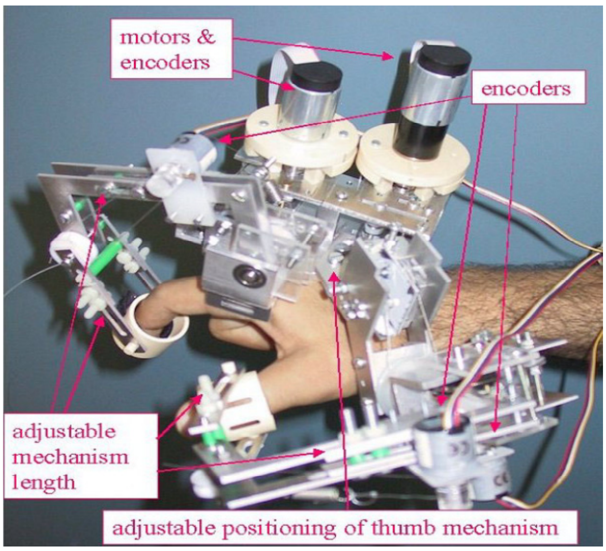


Fig.46. General view of the Robotics Center-Ecole des Mines de Paris Hand (Taken from [19])

II. 19. Delft University Hands

These two devices are haptic master hands with focus on virtual reality and controlling remote slave device [20]. Two different principles for actuation are presented in these devices. The first device (A) controls the index finger for active force feedback whereas the second device (B) controls the index finger for passive force feedback. These actuating principles are different in functionality. Active force feedback allows the operator to feel object stiffness and to manipulate the object. The stiffness displayed in this approach is limited, because no hard-contact simulation is possible. A critical issue is that the actuator could cause injuries to the operator. Passive force feedback allows hard-contact simulation of an object. The actuator cannot exert forces actively on the finger phalanges and therefore secures the operators' safety. No active manipulation is possible and the operator cannot feel the stiffness of the object.

Device A controls 4 DOFs of the human index finger by means of active force feedback. The device consists of 4 circular links, 3 for each flexion/extension movement and 1 for adduction/abduction movement. Each circular link is directly fixed on the finger phalanges and rotates about the finger joints as shown in Fig.47 and Fig.48 . The rotation of circular links about each finger joints cause the movement of the finger phalange. Wire driven mechanisms are used to actuate the circular link only in 1 direction (the flexion movement of joints). The actuation of the extension movement is done by spring.

The actuator part for each DOF consists of a brushless DC motor with a maximum power of 20 [W] that is used to drive the pulley. Both circular link and pulley are connected to drums with the same constant torque spring. The drum connected to the circular link creates a constant clockwise torque on the circular link. On the other side, the drum connected to the pulley creates the same constant anticlockwise torque on the pulley. A pre-tensioned cable connects the pulley to circular link.

Only displacement sensors are taken into account for this haptic device. The encoders on the motors are used to calculate the joints angles of exoskeleton. Position controlling strategy is done with the data received from encoders.

The system is not equipped with any force sensors. It could be dangerous in some cases, due to possible uncontrolled forces transmitted to the human finger. In the experimental tests, high friction forces are reported. The operator felt friction on the human finger during free finger motion.

Device B controls 4 DOFs of the human index finger by means of passive force feedback. The exoskeleton uses the same circular rack on phalanges, but uses a mechanical tape brake at the rolling link for passive force feedback as shown in Fig. 49. The rotation of circular links about each finger joints causes the movement of the finger phalange. The actuator braking module consists of a DC motor with a maximum power of 20 [W]. The actuator pulls the brake cables by a lever mechanism that is placed in the actuating part. A tape brake is created by looping the brake cable around the brake drum. When the actuator pulls the brake cable, the friction between the brake cable and the brake drum locks the movement of tape brake. So, the rotation of circular link is locked.

The same as device A, only displacement sensors are taken into account for this exoskeleton. The rotational position of the finger joints is measured by potentiometers at the drum axis. The positioning of the potentiometers on the frame are shown in Fig 50.

In comparison with device A, the friction forces which are exerted on the human finger phalanges during free finger motion are smaller in device B.

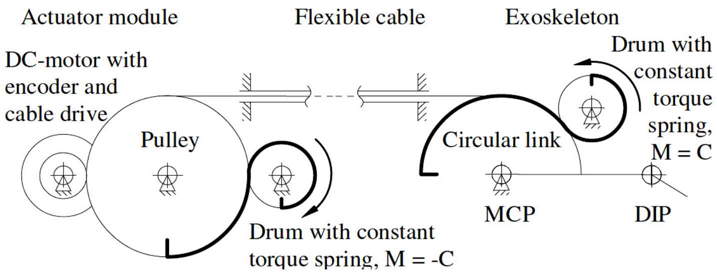


Fig. 47. Scheme for the power transmission of the Delft University “device A” (Taken from [20])

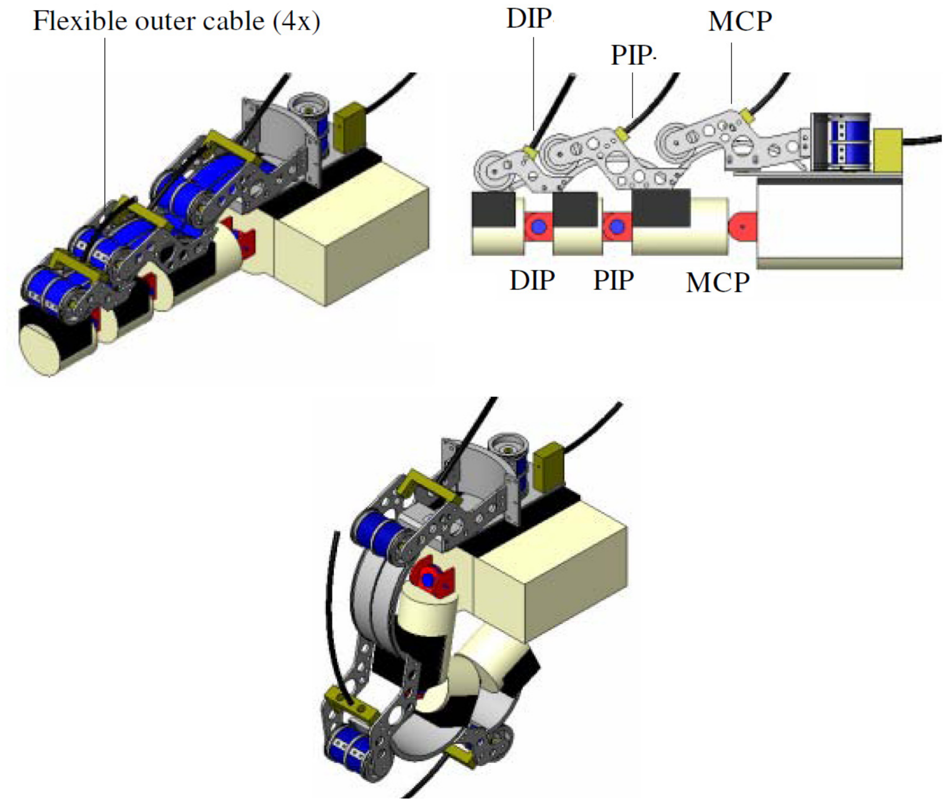


Fig.48. Delft University device A (Taken from [20])

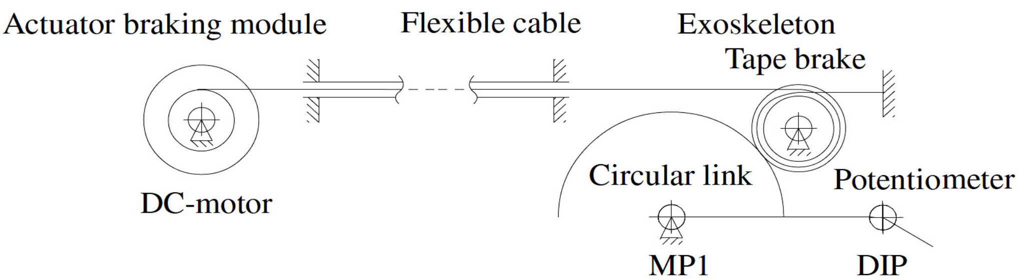


Fig. 49. Scheme for the braking system of the Delft University “device B” (Taken from [20])

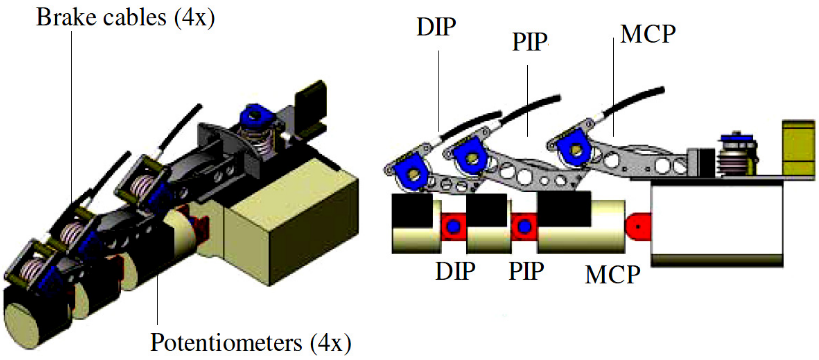


Fig.50. Delft University device B (Taken from [20])

II.20. Rutgers Master II

This is a haptic interface designed for dextrous interactions with virtual environments such as grasping and manipulation of virtual objects [21]. The exoskeleton uses pneumatic direct-drive actuator situated in the palm of the user as shown in Fig.51.

Globally 4 fingers (index, middle, ring and the thumb) are controlled by 4 pneumatic actuators. Each actuator is attached to the base platform in the palm through a universal joint in 2 passive DOFs. Its cylindrical shaft can both moves in and out and rotate about the cylinder axis in 2 DOFs (1 actuated and 1 passive DOF). Finally, the fingertip attachment is connected to the cylinder shaft through a revolute joint in 1 DOF.

The L-shaped platform is placed behind the "middle-line" of the palm and consist of 4 fine-polished surface pneumatic cylinders. The graphite pistons can move smoothly inside the cylinders. The pneumatic actuator provides force up to 16 [N] to human fingertip.

The device can control the position of the joints in a closed loop control scheme by means of 2 Hall sensors and 1 infrared sensor. Two Hall sensors are placed at the bottom of each cylinder and measure the flexion/extension and abduction/adduction angles of each actuator (Fig. 52). An infrared sensor is placed inside the cylinder and measures the translation of the piston inside the cylinder.

Fig. 51. Rutgers Master II (Taken from [21])

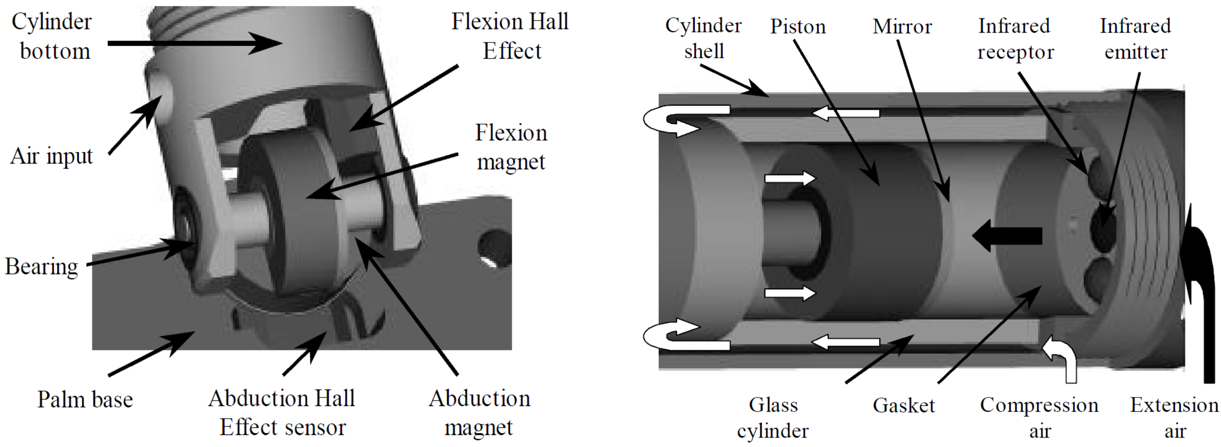


Fig. 52. Sensors used in the Rutgers Master II (Taken from [21])

The mass of the exoskeleton structure is approximately 80 g. This small weight makes the Rutgers Master II glove very comfortable to wear, without undue user fatigue. The main disadvantage of this exoskeleton is its placement, i.e. inside the palm. This fact, decrease the workspace of the exoskeleton and complete grasping is impossible.

II.21. Sensor Glove II (SGII)

This is a haptic exoskeleton type machine named "Sensor Glove II" with focus on virtual reality applications and controlling remote slave devices [22]. The hand adopts special linkage mechanisms to control the movement of fingers.

This 5 finger haptic device is a hand with 20 DOFs. The exoskeleton controls 4 DOFs of each finger. In order to avoid mechanical interference between the finger and exoskeleton during the flexion, this hand exploits a particular slider-crank mechanism for DIP, PIP and MCP joints, as shown in Fig. 53. Each finger contains three block unit that are fixed on the phalanges of the human finger. Each block unit consists of 2 pulleys, 2 links and a slider placed at the end of one link. These 2 external links in combination with 2 human links make a closed chain consisting of 3 revolute joints and 1 prismatic joint. Each closed chain forms a 1-DOF system that could be actuated directly or indirectly, such as through the wire-driven mechanism that is used in this exoskeleton.

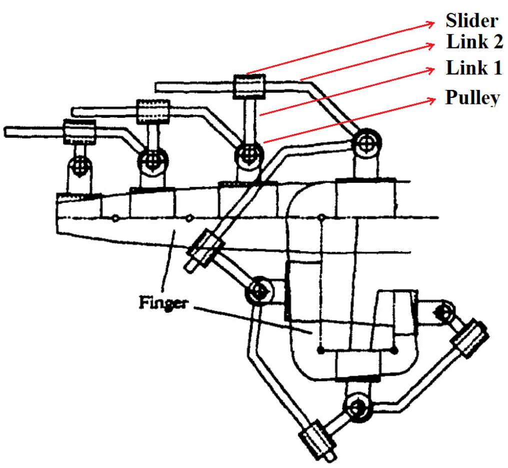


Fig. 53. Scheme of the SG II exoskeleton (Taken from [22])

The exoskeleton can measure the angle of actuator shaft by means of an encoder installed into the actuator. The data gained from rotary encoders are used to compute the angle of the exoskeleton joints. Force controlling can be done using external force sensors (strain gauges) that are installed on the external links. These force sensors measure the perpendicular component of the contact force between the exoskeleton and the human finger. The exoskeleton controls the movement of the human fingers with position controlling when fingers move freely. The control scheme will change from position controlling into force controlling when the slave hand touches an object (in the real or virtual world, depending on the application).

II.22. LRP Master Hand

This is a master hand conceived to remotely control dexterous robot [23].

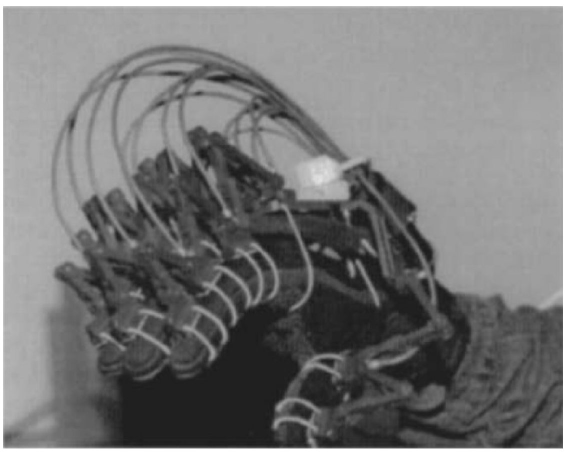
This HE controls 14 DOFs of human hand. The thumb driven by 2 DOFs whereas the other four fingers are driven by 3 DOFs each. The exoskeleton moves the fingers by means of 3 four-bar mechanisms (Fig.54), exploiting the kinematic scheme presented in paragraph II.1. The driving link of each four-bar linkage is actuated by DC motor through a wire-driven mechanism.

The angles of finger joints are measured by potentiometers mounted on the motor shaft. The system controls the movement of exoskeleton only by position sensors and there is not any force sensors in the master hand. It could be dangerous in some cases, due to possible uncontrolled forces transmitted to the wearer's hand.

II.23. Nanjing University Hand

The device is conceived for 2 main applications: the haptic application with focus on the bidirectional force feed-back for virtual reality and the rehabilitation applications [24].

The device interface is a 1 finger hand with 1 actuated DOF (Fig. 55). The flexion/extension movement of DIP, PIP and MCP joints of the index finger are controlled by use of a 4-link serial mechanism that is connected to the human finger only on the fingertip (the same kinematic chain used in II.18, Fig. 43). The abduction/adduction movement of MCP joint is supported passively.



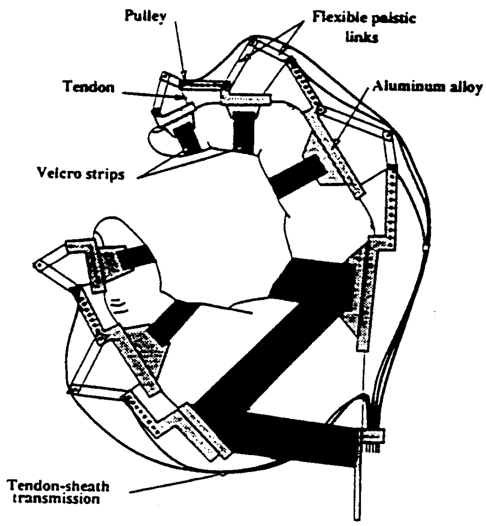


Fig. 54. LRP Master Hand (Taken from [23])

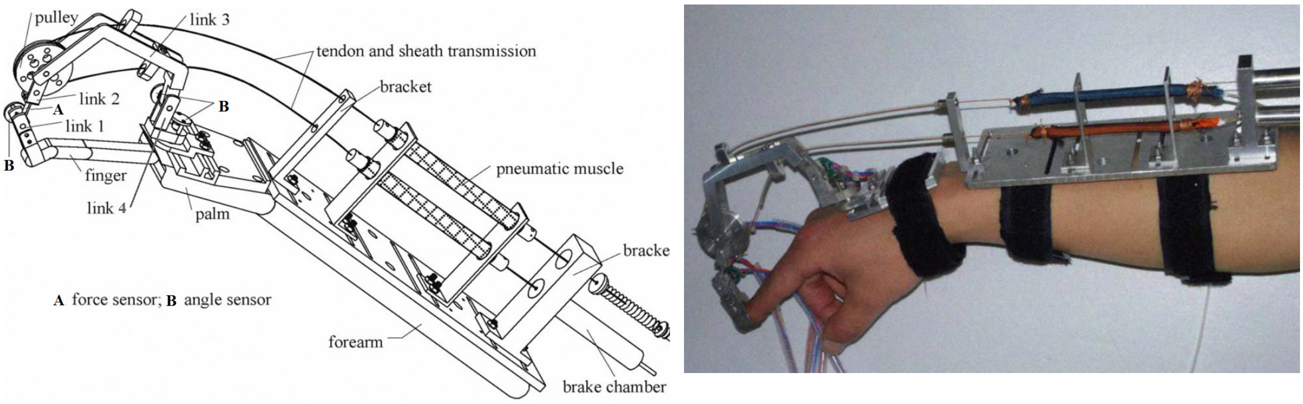


Fig.55. Nanjing University Hand (Taken from [24])

The actuator system is placed on the forearm and consist of 2 pneumatic artificial muscles and a brake system. Tendon drive mechanism is used to actuate the device. One end of the tendon is fixed on the pulley and the other end is tied to the pneumatic muscles. The pulley is fixed to the link 2. The force generated by the artificial muscles is transmitted by the tendons to the pulley, resulting in a torque that causes the rotation of pulley and link 2 which correspondingly leads to a movement of finger joints.

The system is equipped with 2 different kinds of sensors: the position sensors and internal force sensors. The traditional strain gages that are installed on the top and bottom side of cantilevered beam (link 2) are used as force sensors. Four non-contact magneto resistance position sensors are used in device: 3 ones are mounted on the side of links (between link 1 and link 2, link 2 and link 3, link 3 and link 4) and 1 is mounted on the top of pedestal.

The pressure in pneumatic muscles is regulated according to the position and force information gained from sensors. The control procedure for the device can be divided into 2 fields: virtual reality applications and hand rehabilitation applications. The hand function rehabilitation is controlling passive or active movement of finger for both flexion and extension. In passive stage, the finger can flex or extend only under the help of external force. The position-based control strategy is needed at this stage which mainly exercises the joint mobility. At the second stage, the active training, the force-based control strategy is needed when the finger can move actively. The finger functions are not entirely recovered. The bidirectional feedback dataglove supplies resistance against movement to excise the finger muscle and strengthen its power. For virtual reality application, the pressure in pneumatic muscles is regulated according to the virtual force calculated by controller.

II.24. University of Tsukuba Hand

This is an assistive HE that supports human hand and wrist activities [25, 40]. The system uses bioelectric potential to control the movement of the exoskeleton.

The device controls 8 DOFs of human hand. The index finger is supported by 3 actuated DOFs for the flexion/extension of the 3 joints, the combination of middle, ring and little fingers is supported by 3 actuated DOFs (for the same flexion/extension movements).

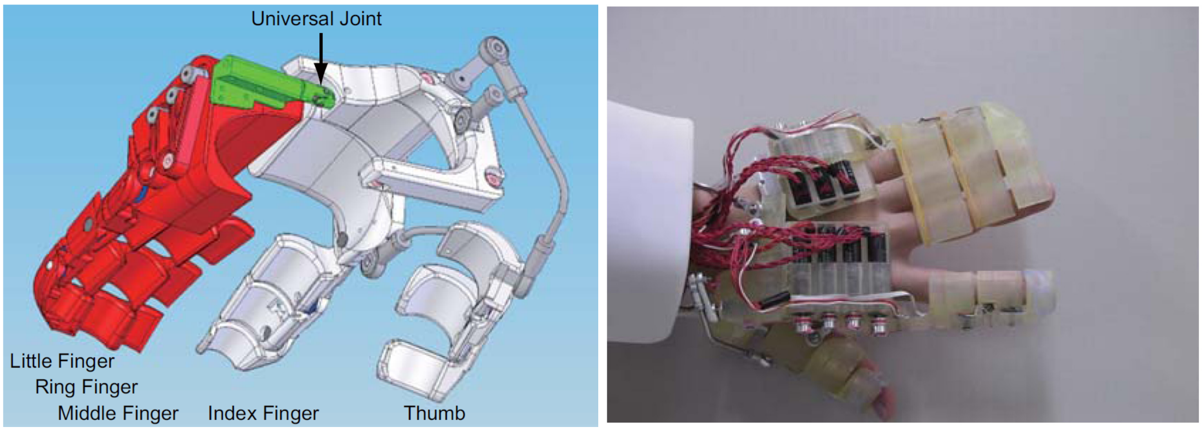


Fig.56. Scheme and picture of the University of Tsukuba Hand (Taken from [25])

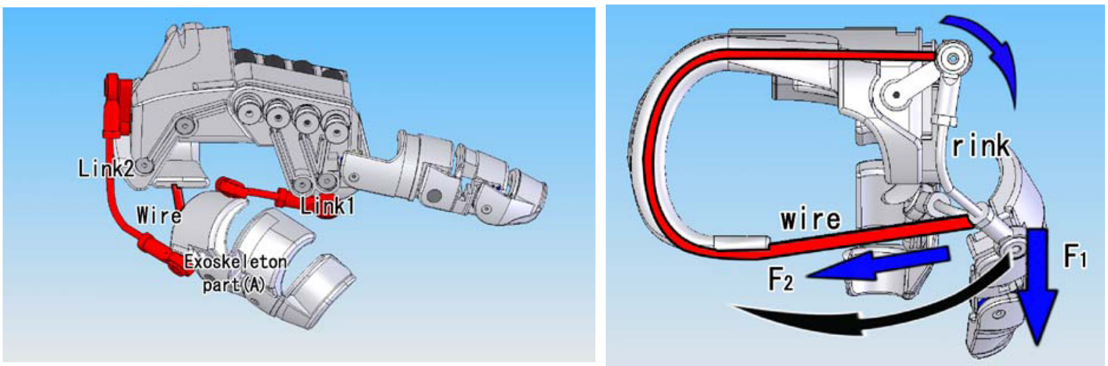


Fig. 57. Link allocation for thumb support (Taken from [40])

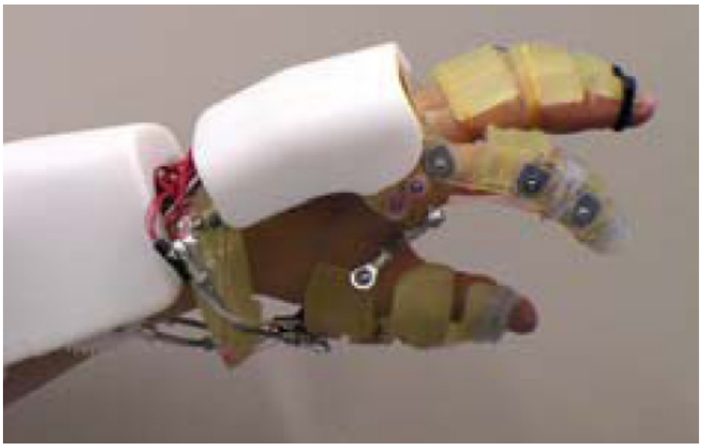


Fig.58. University of Tsukuba Hand (Taken from [25])

The index finger and the combination of 3 fingers are connected to the frame with universal joints, which allow passive movements of abduction/adduction as well (Fig.56).

The thumb is supported by 2 actuated DOFs. The thumb driving mechanism consists of two links, two wires and two actuators. The CMC joint is driven by two links, one wire and one actuator shown in Fig.57. The link 2 driven by an actuator is used to support opposition motion. The wire is arranged to be parallel to flexor pollicis brevis and opponens pollicis muscle, i.e. those working for the opposition. The flexion/extension movement of IP and MCP joints are coupled and actuated by another wire and another actuator.

The main mechanical characteristic of this exoskeleton is its placement. The mechanism of this exoskeleton is placed on the side of the fingers (Fig.58). The main disadvantage of some exoskeletons that are placed on the dorsal side of fingers is the difficulty involved in attaching them to the fingers, that is these exoskeletons are required to match the rotational center of their joints to that of the human joints by different kinds of RCMs. In this exoskeleton, the mechanism is placed on the side of the finger and the joints of the exoskeleton coincide with the human finger joints. By this kind of structure, no RCM mechanism is required, thus allowing less complex structure and less friction forces of the device. The main drawbacks of this structure is its availability for some fingers. This happens because it is only possible to place this machine beside the thumb, index and little finger. So, for controlling the 3^{rd} and 4^{th} fingers, that are not attached to the machine and controlled directly, the system has a special link that combined the movement of 3^{rd}, 4^{th} and 5^{th} fingers.The actuator part is placed on the forearm and consists of 3 DC motors for the index finger, 3 DC motors for the combination of 3^{rd}, 4^{th} and 5^{th} fingers and 2 DC motors for the thumb. Force transmission is done by means of a wire-driven mechanism.

The system is equipped with position sensors, and the force control is done by controlling the current of DC motors. The exoskeleton joint angles are measured by rotary potentiometers directly installed on each joint. In addition to joint measurement, a rotary encoder is installed into the shaft of the DC motors. It is possible to detect mechanical failure by comparing values gained by each angular position sensors. The electric current of DC motors is controlled by the main controller system that enables the system to control the force applied to the human finger. The exoskeleton controls the movement of fingers by two modes: finger-following control and grasping force control. In finger-following mode the system does not disturb human finger motion when power support is not necessary so that human finger can move as if it wore nothing. In grasping force mode, the human finger receives the required grasping force from the exoskeleton. The force applied from machine to the human hand is controlled by a cap with two 3-axis accelerometers (Fig. 59). Two accelerometers are installed on the forehead and back of user head in order to distinguish three rotation angles of users head. The system uses the data received by these accelerometers to control the amount of force applied to the human hand. The grasping force is discretely increasing up to the maximum grasping force as the head rotation is repeated in the same direction. Once the system observes the head rotation in the opposite direction, the hand releases the grasping object.

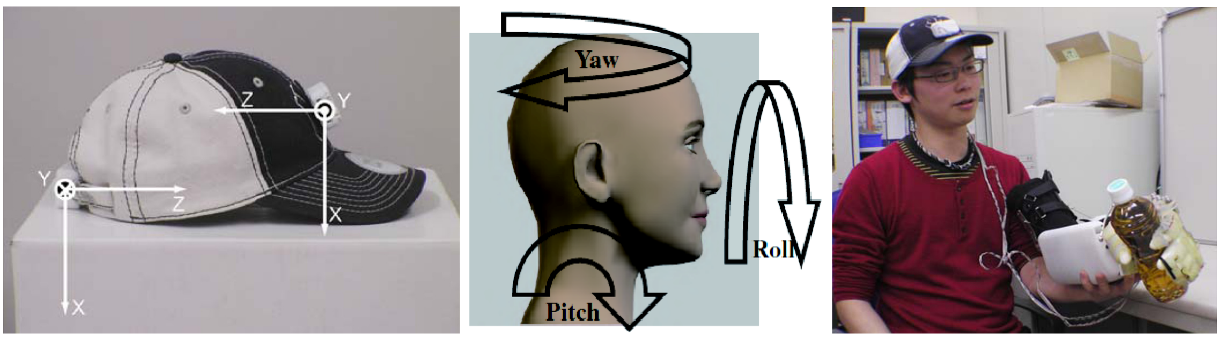


Fig. 59. Cap and accelerometer axis for controlling the University of Tsukuba Hand (Taken from [40])

This assistive exoskeleton supports human hand with different kind of structures. The innovation of placing the mechanism on the side of the fingers causes the joint of exoskeleton coincides with the human finger joints. Further, since it is not possible to place this mechanism beside 3^{rd} and 4^{th} fingers, the exoskeleton combines the movement of 3^{rd}, 4^{th} and 5^{th} fingers by using special link.

II.25. Okayama University Hand

This assistive device was designed with focus on hand grasping in order to support ADLs [26, 41, 42]. The device is equipped with pneumatic artificial rubber muscles as actuators.

This HE controls 4 DOFs of human fingers (the index, middle, ring and little fingers). Each finger is supported with 1 DOF: the flexion/extension of DIP, PIP and MCP joints is actuated by means of a single rubber muscle, by adopting an under-actuated solution (no mechanical coupling among the joints/phalanges is introduced). The thumb is supported with 2 DOFs: the flexion/extension of IP, MCP and CMC joints is actuated by means of a rubber muscle (identically to the other fingers) and the abduction/adduction of CMC joint is actuated by another rubber muscle. The device basically consists of a glove and its actuators, i.e. the curved rubber muscles placed on the backside of the fingers (to actuate the fingers' flexion/extension) and the linear rubber muscle placed in the root of thumb (to actuate the thumb abduction/adduction), as shown in Fig. 60. There is no mechanism to couple the joints' movements. The actuator are directly attached to the glove and the deformation of the muscles' body provide the glove and human finger movements.

The curved type rubber muscle consists of a rubber tube and polyester bellows. For inhibiting expansion in the axial direction, the polyester fiber bellows is reinforced with a fiber tape (Fig.61 a). The length of the rubber muscle is decided by considering the length of human finger. By the reinforcement, when the compressed air is supplied into the rubber muscle, the rubber muscle curves to the reinforced direction shown in Fig. 61 (b,c).

The linear type rubber muscle consists of a rubber tube and polyester bellows but, differently from the curved rubber muscle, there is not any fiber tape as a reinforcement Fig. 62 (a). Therefore, when the compressed air is supplied, the rubber muscle extends towards the axial direction, as shown in Fig. 62 (b). According to this axial expansion movement, the motion of root of thumb (abduction/adduction movements) can be realized only by applying a given force in on fixed direction.

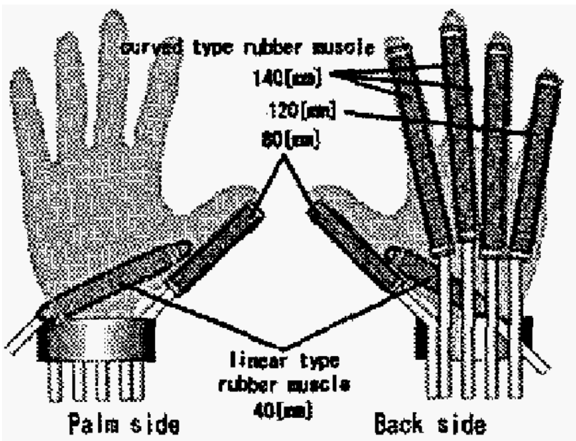


Fig. 60. Scheme of the Okayama University assistive device (Taken from [26])

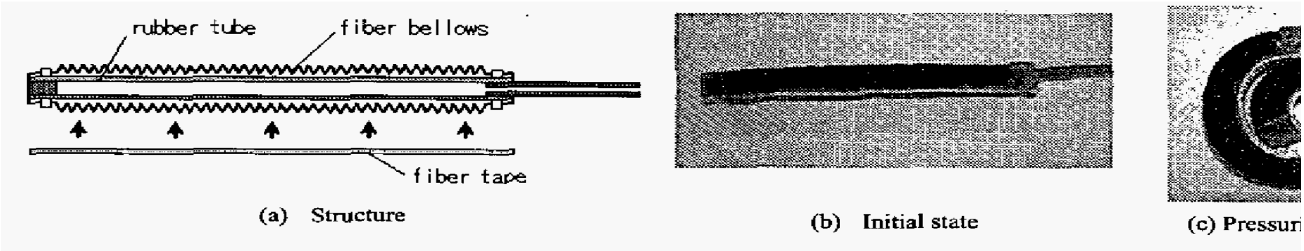


Fig. 61. Curved type rubber muscle (Taken from [26])

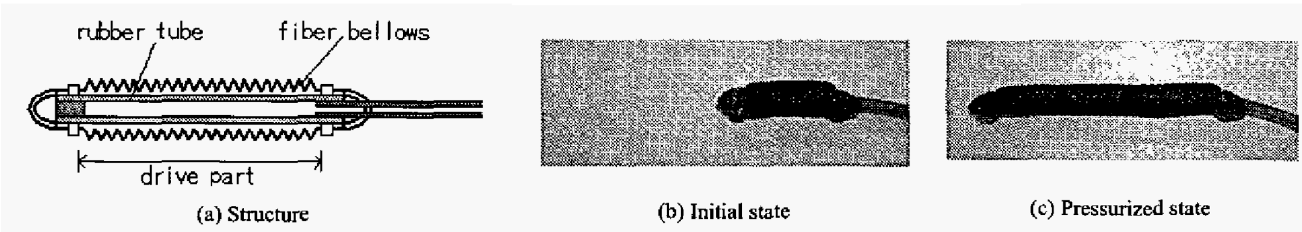


Fig. 62. Linear type rubber muscle (Taken from [26])

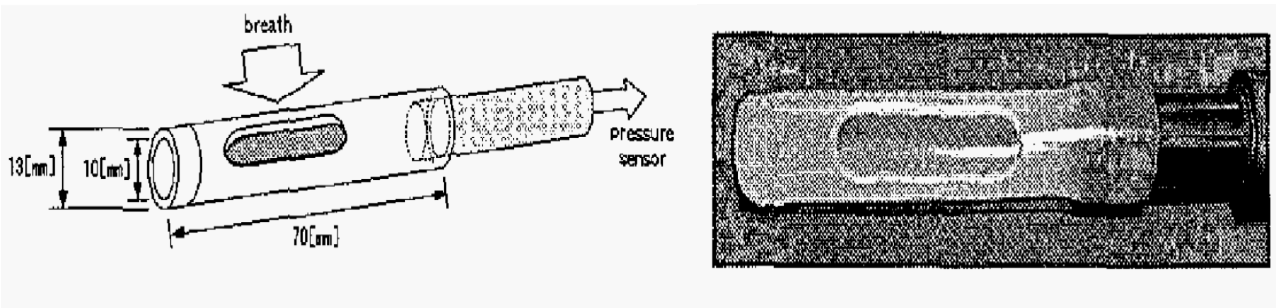


Fig. 63. Expiration switch (Taken from [26])

An expiration switch, made of a silicone rubber tube (Fig. 63), is used to control the air pressure in this exoskeleton. One end of tube is connected to the rubber muscle, and the other end is connected with an air pressure sensor.

In addition to air pressure sensor, the system is equipped with tactile force sensor at the fingertips that measure the forces applied to the fingers in order to implement a force control procedure (the force exerted to the finger is controlled by the pressure injected into the rubber muscles).

II.26. PneoGlove

This is an assistive device with focus on grasp activities [27]. The system appears as a glove that controls finger extension by means of a pneumatic actuator (the flexion movement is not actively supported). Additionally, EMG signals are incorporated to allow active participation of the user.

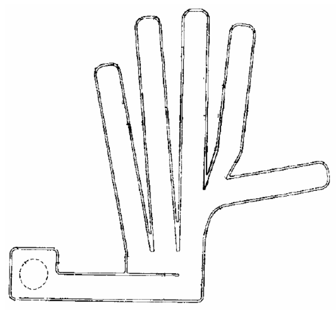


Fig. 64: Bladder layout of the PneoGlove

Fig. 65: Pictures of the PneoGlove (Taken from [27])

This HE controls 1 DOF of human hand. The extension of the DIP, PIP and MCP joints of each finger is actuated by a pneumatic bladder, adopting an under-actuated solution (both for the finger joints and the fingers themselves): indeed the glove contains a single chamber bladder that acts as a single unit during inflation, as shown in Fig. 64. There is no mechanism to couple the joints' movements. The actuator are directly attached to the glove and the deformation of the bladder provides the glove and human finger movements.

This bladder is sewn onto the palmar side of a nylon/lycra glove with a dorsal zipper to ease donning of the glove. The length of the digits allows for a variety of finger lengths such that shorter fingers will leave space at the tip of the finger (Fig. 65). Inflation of the air bladder forces straightening of the bladder channels, thereby assisting the extension of the fingers.

The system is equipped with EMG electrodes that are placed on the flexor digitorum superficialis and extensor digitorum communis muscles of the gloved arm to sample muscle activity. For position controlling, angle of the PIP joint of the index finger and MCP joint of the middle finger are measured using electrogoniometer sensors.

The bladder is connected through a servo valve to a pressure reservoir. The servo valve allows pressures between 0-5 psi to inflate the glove. Another port on the bladder is connected to a pressure relief valve that opens at 6.1 psi to avoid over inflation. The controller regulates the pressure necessary to maintain the required angle for both the PIP and MCP joints during reaching. When the fingers are extended further then the set point, pressure to the glove is reduced to maintain the necessary joint angles. EMG feedback may be incorporated to allow active participation of the user.

Two different control strategies are employed for the grasp portion of the grasp-and-release training dependent on whether virtual or actual objects are used. When virtual objects are displayed to the user, the system monitors the point at which the hand is sufficiently extended to hold the object. When this condition is met, a signal is sent to the virtual reality (VR) program to allow grasp of the object. When the virtual object is held, the glove control system continues to regulate pressure to maintain the desired joint angles in order to simulate holding a real object. The release portion of the grasp-and-release paradigm is accomplished by monitoring EMG activity.

The device is powered by pneumatic pressure to assist the wearer only in finger extension. The exoskeleton does not have any ability to actuate the fingers in the flexion.

II.27. Vanderbilt University Hand

This is an assistive HE to fit over the gloved hand of an astronaut and to offset the stiffness of the pressurized space unit [28].

This 3 finger assistive device allows independent movement of the index and middle, each one in 1 DOF, and the combination of ring and little finger, in 1 DOF as well (Fig. 66).

Each finger of the exoskeleton is controlled by 1 DOF. So the movement of MCP and PIP joint are coupled, whereas the DIP movement is inhibited. The exoskeleton is connected to the human finger by means of 2 semicircular brackets. The second bracket is located on the DIP joint, so that the distal and the middle phalanges move together. The exoskeleton uses 2 coupled six-bar mechanisms in each finger for flexion/extension of MCP and PIP joints (links 1-6 for the first six-bar mechanism and links 6, 8-12 for the second one). The connection between the two six-bar mechanisms is achieved by the introduction of a further link (link 7), as shown in Fig. 67.

The actuator unit consists of 3 DC motors and wire driven mechanisms that are applied to actuate the input link of each finger in direction of flexion. The stiffness of the space suit glove itself provides the force for the extension.

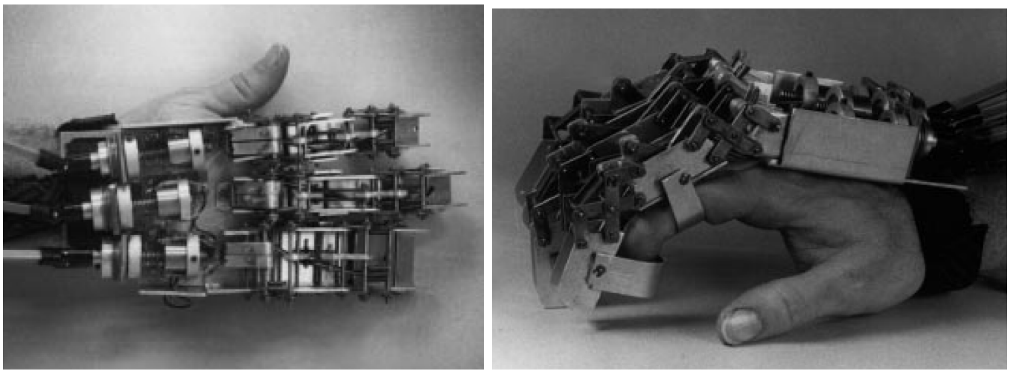


Fig. 66. Vanderbilt University assistive device (Taken from [28])

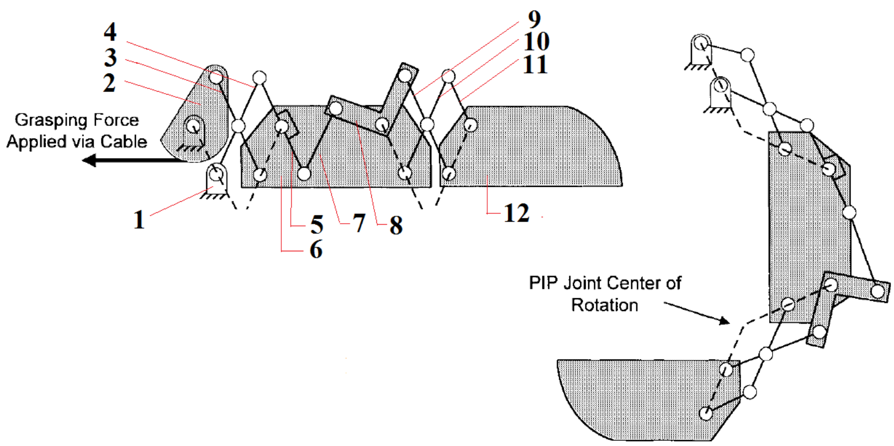


Fig. 67. Coupled six-bar mechanisms used in the Vanderbilt University Hand (Taken from [28])

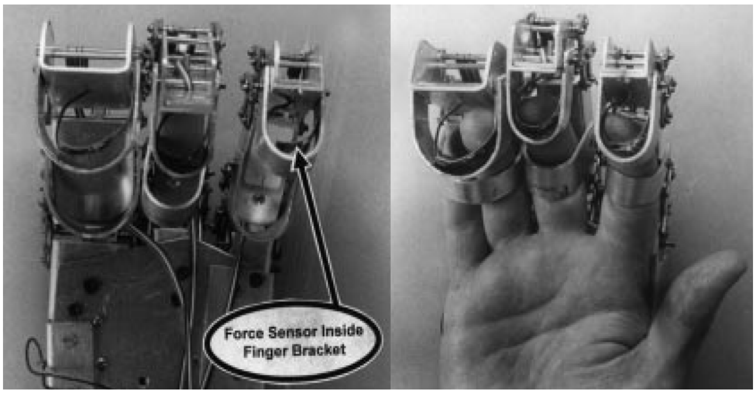


Fig. 68. Placement of the force sensors in the Vanderbilt University Hand (Taken from [28])

The exoskeleton is equipped with external force sensors inside the last finger bracket (Fig. 68). It consists of a strip of brass gage stock that is bent into a "J" shape and fits inside the distal finger bracket of each exoskeleton finger. Each force sensor measures the force exerted from the human fingertip to the exoskeleton in the flexion direction. The movement of this exoskeleton is controlled by the amount of forces exerted to the force sensor. Two pressure threshold levels set in the software are necessary with this method. If the pressure exerted from the finger to sensor is lower than the first threshold, the motor makes the appropriate finger open. If the pressure level from a finger to sensor is between the first and second threshold, the motor stops turning and the to the mechanism position is locked. As the contact force increases further the second threshold, the finger is driven to close.

II.28. Tokyo Institute of Technology Hand

This is an assistive device intended to amplify the force generated by the user during grasp activities[29]. The device is equipped with pneumatic artificial rubber muscles as actuators. Additionally, sensors to detect EMG signals are incorporated to allow active participation of the users (Fig.69).

The HE controls 10 DOFs of human hand. Each finger is supported by 2 DOFs: the flexion/extension of MCP joint is actuated by means of a single rubber muscle and the flexion/extension of DIP and PIP joints is actuated by means of another single rubber muscle, by adopting an under actuated solution (no mechanical coupling among the joints/phalanges is introduced) as shown in Fig.70.

The thumb is supported by 2 DOFs as well: the flexion/extension of IP and MCP joints are actuated by means of a rubber muscle (identically to the other fingers) and the abduction/adduction movement of CMC joint is actuated by another pneumatic unit called manifer. The manifer realized rotation of the thumb (abduction/adduction) by pulling the artificial rubber muscle with the wire suspended by the pulleys (Fig.71).

The device is placed above the fingers and is connected to the finger phalanges by means of finger holder. To mimic the motion of the wearer, the rotation center of the device coincides with the rotation center of the wearer finger by means of a passive prismatic joints. By using this slider-crack mechanism, the length of the link is passively adjusted to avoid interference.

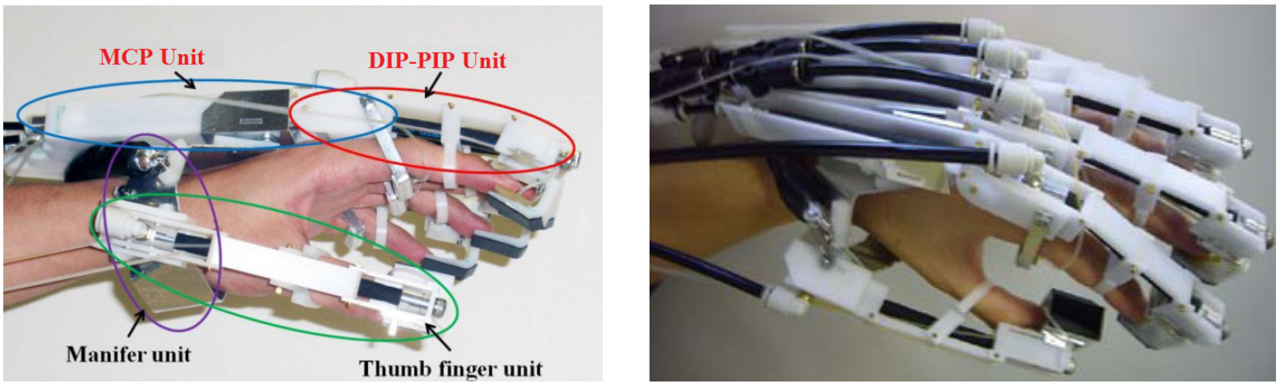


Fig.69 power amplified glove (Taken from [29])

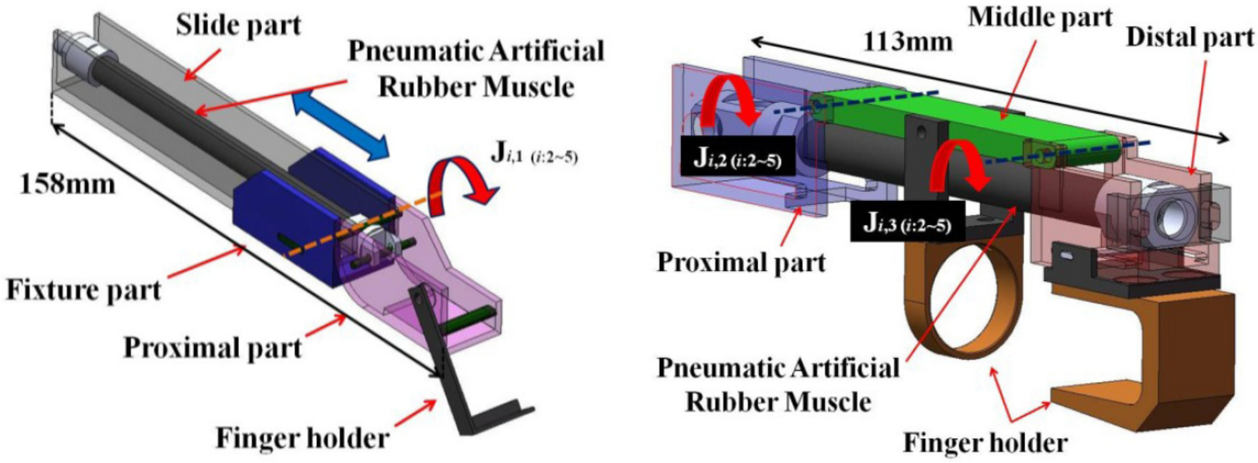


Fig.70. Finger units (left: MCP unit, right: DIP-PIP unit) (Taken from [29])

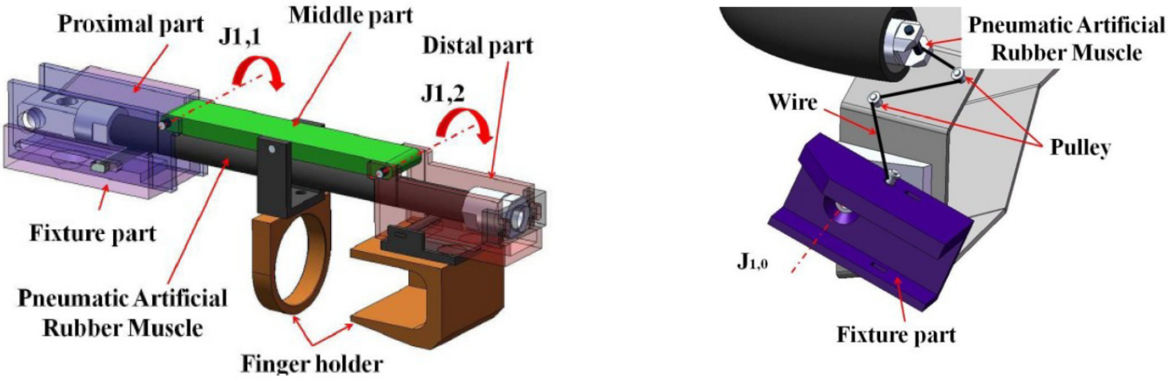


Fig.71 Thumb and manifer unit (Taken from [29])

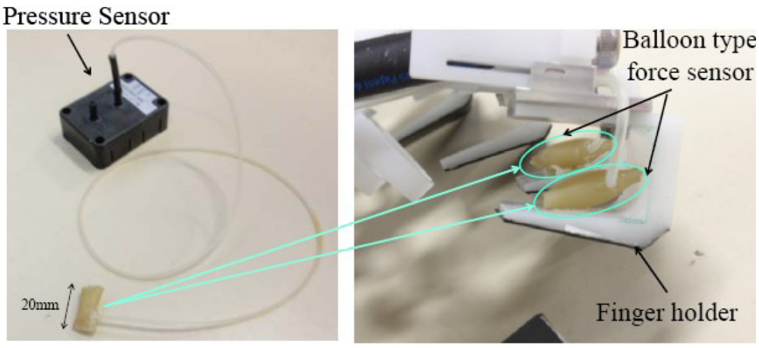


Fig. 72. Photograph of balloon sensor (Taken from [29])

Fig.73. Photograph of underwater experiment (Taken from [29])

The device is equipped with 2 pneumatic external force sensors for each finger. These force sensors are located between human finger and exoskeleton (one is placed at the tip of each finger and the other is placed between proximal phalanxes and the device). These pneumatic force sensors are composed of a rubber tube. One end of the tube is bonded with epoxy and the other end is connected to a pressure sensor (Fig. 72). Because there is not any electrical component or sensor connected to the device, the glove works well even after gotten wet (completely floated in the water) as shown in Fig.73.

The purpose of this assistive glove is to amplify the generated force by the wearer. Therefore, the force exerted by the human finger to the pneumatic force sensors is measured and detected force provided by the HE will amplified. Additionally, the system is equipped with EMG electrodes to sample muscle activities and to evaluate the power-assist performance. The system is not equipped with any position sensors.

III. Discussion

Depending on the specific application to be addressed, the designer of a new HE must face a wide range of choices, such as: the numbers of DOFs (per single finger or whole hand), numbers of actuators, system architecture, transmission system, control scheme etc. It should be taken into account that a given decision on each aspect contains some advantages and drawbacks and also it can affect other aspects of designing. In a few words, selecting a given specific solution can solve a group of problems related to one or some aspects of designing, but this selection could trigger other kinds of problems or limitations in other aspects. The analysis of the state-of-art (i.e. the first step to be theoretically followed when designing a new technological product) may help in defining some key issues and the related solutions by observing the existent products/prototypes. The literature proposes a large number of HEs that generally present some common characteristics and many special peculiarities concerning their mechanics, electronics (control) and working principle as reported in previous sections. In this section, the main aspects that are involved in designing HEs are reviewed and the critical issues provided by the literature analysis are discussed.

The first key factor that must be taken into account is relative to the kinematics of the system. Indeed, the designer must choose:

The first key factor that must be taken into account is relative to the kinematics of the system. Indeed, the designer must choose:

- the number of DOFs of the mechanism which guides the functions of a single finger (recalling that the human finger has 3 DOFs related to the phalanges' flexion/extension and 1 DOF for the MCP adduction/abduction);
- which joint movements can be possibly coupled (e.g. for a finger having 2 DOFs for flexion/extension, the coupling should occur between the DIP and PIP joints or between the PIP and MCP joints?);
- whether providing a number of actuators to control all the DOFs of the finger exoskeleton or designing an under-actuated mechanism (i.e. one or more DOFs are controlled exploiting only the dynamics of the human finger and/or HE);
- how many finger mechanisms will form the overall HEs, and how many of them must be controlled independently.

The different HEs proposed in the literature use a different number of DOFs according to their applications, design, limitations or characteristics. There are a few devices that control 20 DOFs of the hand movement (complete movement of all fingers to replicate the overall human hand movements). Other devices use different coupling mechanisms to couple with the movement of human finger joints, and other systems leave some joints free (i.e. uncontrolled). Coupling between the joints of a single finger is done by means of different mechanical solutions such as cables and pulleys or rigid linkage mechanisms. In addition to the mentioned coupling in a single finger, some HEs actuate the combination of some fingers together (for instance, the 2^{nd}, 3^{rd}, 4^{th} and 5^{th} fingers are controlled by means of one actuator). It is worth mentioning that in a number of HEs different kind of under-actuated mechanisms are proposed as simple solution to approximately control the finger movement.

HEs control the movement of fingers by means of a series of links which could be placed above the human fingers, beside the fingers or inside the palm. Each solution contains some advantages and drawbacks according to their placement relative to the human fingers. The first critical problem that must be solved for those devices that are placed above the fingers is the mechanical interference between the machine links and the anatomical parts. Different devices use different kind of RCM mechanisms such as six-bar mechanisms, Circuitous Joints or slider/crank-type mechanisms to make the mechanism centre of motion coincide with the human joint axis while avoiding mechanical interference. For the HEs that are placed above the fingers, a common and very simple solution to transmit motion is based on a four-bar mechanism scheme, even though this approach does not guarantee a priori the interference avoidance. The solution must be selected according to the applications of the given HE. For instance, if a master hand with 1 DOF per finger has to be designed, position control and force control only in the distal phalange of human finger are needed. So, one possible solution could be a HE with three coupled six-bar mechanisms for each finger [28], which can mimic the finger movement and is connected to the finger only in the distal phalange. In this case, one cannot use three coupled four-bar mechanisms as in [2], for instance. Each four-bar mechanism indeed requires also anatomical parts (two phalanges and a revolute joint) and the resulting system must therefore be connected also to the first and second human phalanges. where the user will feel force that could be disturbing. Because of this fact, HEs that use four-bar mechanisms are usually used for rehabilitation purposes [2, 3, 4]. But HEs that are used for haptic or master devices, whose main focus is on the position and force control of the distal phalange, use coincident with the center of rotation of the human finger. This appears to be a great benefit, but this solution needs room beside the fingers that is not always available (e.g. between 2^{nd} and 3^{rd}, 3^{rd} and 4^{th} fingers). The exoskeletons that are placed inside the palm do not need any RCM mechanisms [21] as well, so they could be very simple and light weight. The main disadvantage of these kinds of HEs is that their placement will decrease the workspace of the exoskeleton and makes complete grasping impossible.

Other major key factors of the devices are the actuators and the transmission systems. The exoskeletons illustrated in this report used pneumatic actuators or electric actuators, whereas no hydraulic systems were found in the literature. The HEs that use pneumatic actuators could be more light weight than those using electric actuators. But, in general, they need a big external pump and compressor which is a major drawbacks. In order to keep the weight of the exoskeletons limited, the actuators are usually located far from the exoskeleton (e.g. placed on a frame fixed to the user's forearm). The power is transmitted to the exoskeleton attached to the fingers by means of different transmission systems such as wire-driven mechanisms or linkage mechanisms. It is worth mentioning that in some devices the use of very lightweight electric motors (ultrasonic motors) makes it possible to place the actuator directly above the fingers.

HEs can exploit different control inputs by the wearer to control the finger functions, e.g. EMG-signals gained from human muscles or the movements measured on the other patient's hand (using the so-called self motion control), basically depending on the application for which the system is designed. In addition to the input command sensors, exoskeletons need some position sensors and force sensors to implement proper motion control strategies (typically position control or force control or a combination of both). For position controlling, most exoskeletons use incremental encoders integrated in the electric motors and the joint angles are calculated by means of the kinematic scheme of the mechanism. Some exoskeletons use sensors (e.g. potentiometers, Hall effect sensors, absolute encoders) directly placed on joints to measure the relative angular position of the connected links. Also the force sensors can be placed in different parts of the exoskeleton, depending on their characteristics and working principle. In some devices, they are directly placed between the HE and the human fingers to measure the contact force. Unfortunately, in this arrangement the sensors do not distinguish between forces exerted by the user and external forces. Thus, during contact with the environment, it becomes impossible to recognize the user's intention. Additional force sensor at every possible contact surface could detect external forces, but would causes losing direct contact between human finger and the subject. Additionally, due to mechanical reasons and nature of these sensors, the angle of the force application of the force varies from 40 to 70 degrees. Because sensor in use are calibrated for perpendicular force applications, measured forces have to be corrected depending on the joint angle. In other cases the grasping force is calculated by measuring the tension of cables on wire-driven mechanisms.. Finally, in some devices whose kinematic scheme and friction models are accurate enough, the force exerted on the human fingers is computed and controlled by measuring and controlling the current draining of the electric motors (whose torque constant must be known). Unfortunately, modeling or measuring the force (or power) lost by friction are very difficult tasks, so that the systems that exploit this strategy are generally not very accurate in force control.

IV. Conclusion

This paper presented a survey of a significant number of works on HEs. Different rehabilitation HEs which are suitable for various kinds of protocols in rehabilitation procedures have been reviewed. Some other HEs that are designed for other applications and purposes have been considered as well, particularly because of their close connection and high similarity of their mechanical parts and control procedures with rehabilitation exoskeletons.

The state-of-the-art of HE is provided by describing the systems' kinematic, the actuator system, transmission part and control scheme of the most representative solutions from the literature. Specific applications ask for specific architectures. According to the application of the exoskeleton, one finger can have from 1 to 4 DOFs and the whole HE from 1 to 5 fingers. In other words, there are HEs formed by a single finger with 2 DOF [2] and HEs having 5 fingers and 20 DOFs [3]. In addition to different DOFs, various kind of actuators and transmission systems are used. In some exoskeletons, the links are driven by means of pneumatic cylinders while in others ones the links are driven by electrical motors. Usually electrical motors are located far from the exoskeleton and actuate it by transmission systems such as wire-driven mechanisms or linkage mechanisms. On the other side, by utilizing some particular kind of electrical motors (ultrasonic motors), it is possible to locate the motors above the finger and directly actuate the exoskeleton.

With reviewing different HEs suitable for specific applications (e.g. rehabilitation, haptic or assistive), one can achieve a wide range of information about the mechanical characteristics and control procedures of each HE. Additionally, it is possible to get familiar with advantages, drawbacks and general design issues that are peculiar characteristics of each HE.

Eventually, a substantial amount of work has been done, but the structure field is still unclear. Some main questions still remain: Which structure is more suitable for a particular purpose? What are the main concerns about designing the HE for a particular application? How many DOFs or contact points are suitable for a particular HE? These questions are still widely open, in part because there is not any systematic classification on different HEs that are applied for different purposes.

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