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Review:

Humanoid Robot Hand and its Applied Research

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Humanoid robot hands are expected to replace human hands in the dexterous manipulation of objects. This paper presents a review of humanoid robot hand research and development. Humanoid hands are also applied to multifingered haptic interfaces, hand rehabilitation support systems, sEMG prosthetic hands, telepalpation systems, etc. The developed application systems in our group are briefly introduced.

Keywords: robot hand, haptics, hand rehabilitation, myoelectric prosthetic hand, telepalpation

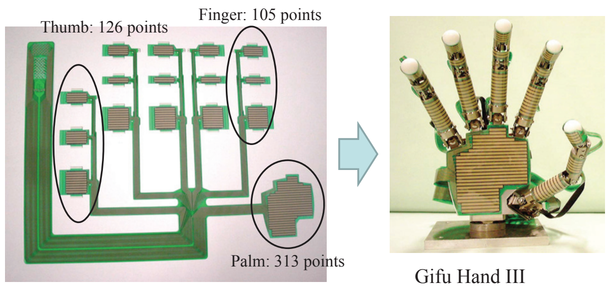


Fig. 1. Gifu Hand III and distributed tactile sensors.

1. Introduction

Future humanoid robots will execute various complicated tasks based on instructions received from human users. These robots will be equipped with anthropomorphic robotic hands much like the human hand. The robots will eventually supplant human labor in the execution of intricate and dangerous tasks in areas such as manufacturing and space and deep ocean exploration.

2. Robot Hand

2.1. History of Development

Many multifingered robot hands have been developed (e.g., the Stanford-JPL hand [1] and the Utah/MIT hand [2]). These robot hands are driven by actuators located remotely from the robotic hand frame and are connected by tendon cables. The elasticity of the tendon cables can cause inaccurate joint angle control, and the long wiring of such cables may obstruct the robot's motion when the hand is attached to the tip of the robotic arm. These hands have been problematic commercial products, particularly in terms of maintenance, owing to their mechanical complexity.

To solve these problems, robotic hands in which the actuators are built directly into the hand have been developed (e.g., the Omni hand [3] and the DLR hand [4]). However, these hands present a challenge in that their movement is unlike that of the human hand because the number of fingers in the robotic hand and the number of joints in the finger are insufficient. Many reports on the use of tactile sensors [5, 6] have been presented, all of which attempted to realize adequate object manipulation involving contact with the fingers and palm of a robotic hand.

2.2. Gifu Hand

The authors' group developed the Gifu Hand I [7], the Gifu Hand II [8], and the Gifu Hand III [9], as well as the kinematic humanoid (KH) hand type S [10]. These were developed to provide a standard robot hand for use in the study of grasping and dexterous manipulation. The Gifu Hand II was the first robotic hand equipped with six-axis force sensors at the fingertips and was covered by distributed tactile sensors. **Fig. 1** shows the distributed tactile sensors with 895 detection points and the Gifu Hand III covered by the tactile sensor. The Gifu Hand series has five-finger hands driven by built-in servomotors that have 20 joints with 16 degree of freedom (DOF). The design concepts for these robot hands are as follows:

(1) Size: it is desirable that the robot hand resemble the human hand in size and geometry for purposes of skillful manipulation.

(2) Finger DOF: the number of joints and the DOF in the robot hand are similar to those of the human hand.

(3) Opposability of the thumb: the thumb of a robot hand is opposed to the four other fingers, enabling the hand to manipulate objects dexterously like the human hand.

(4) Force sensor: the robot hand grasps and manipulates objects dexterously with the help of tactile sensors and force sensors in the fingers.

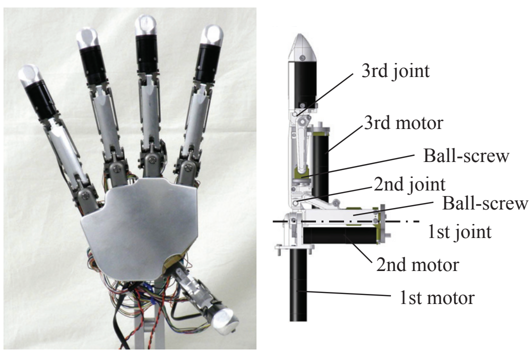


Fig. 2. Robot hand with high fingertip force.

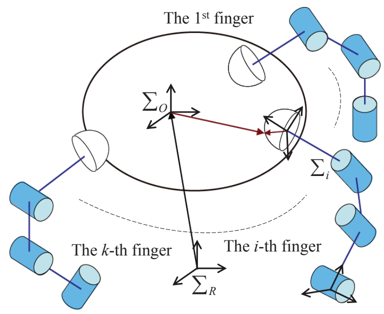


Fig. 3. Model of multifingered robotic hand.

(5) Built-in servomotor method: the motion of the robot arm is not disturbed by the robot hand, and the robot hand is easily attached to the robot arm.

(6) Unit design of the finger: each joint must be modular, and each finger must be a unit in order to realize easy maintenance of the robot hand.

2.3. High-Power Hand

Most robot hands have a lower fingertip force than the human hand. The robot has a tradeoff relationship between the grasping force and the size of the robot hand. It is unable to grasp a heavy load. Several robot hands with high fingertip force have been developed [11, 12]. However, these robot hands have a lower DOF than human ones. They cannot sufficiently grasp in a dexterous manner. The authors' group developed a high-power hand [13]. A high-output fingertip force of 100 N can be generated by a ball screw mechanism that has high-accuracy positioning and high joint torque. The robot hand and finger mechanism are shown in **Fig. 2**. The finger has three joints and three degrees of freedom. The first joint permits an adduction/abduction motion. Because the second and third joints permit flexion/extension using the ball screw, the robot hand can grasp with high fingertip force.

3. Control of Robot Hand

When a robot hand grasps and manipulates an object, the hand and object interact at several contact points. Since contact conditions vary according to the point contact, line contact, surface contact, and the existence or nonexistence of friction at the contact point, the constraint conditions that the object receives are also diverse. Basic kinematics and dynamics in terms of the grasp of a multifingered robotic hand have been established. An introduction to these topics is available in [14, 15].

3.1. Dynamics of Robot Hands

Dynamic model is used widely in the simulation of robot motion, analysis of robot hand structures, and design of control algorithms. The motion equation of the hand system can be presented by combining each of these of the hand and the object under the nonholonomic constraint of the grasp, as follows:

$$\boldsymbol{M}_O(\boldsymbol{r}_O)\dot{\boldsymbol{v}}_O+\boldsymbol{C}_O(\boldsymbol{r}_O,\dot{\boldsymbol{r}}_O)\boldsymbol{v}_O+\boldsymbol{g}_O(\boldsymbol{r}_O)=\boldsymbol{G}_C\boldsymbol{\lambda} \quad (1)$$

$$\boldsymbol{M}_F\ddot{\boldsymbol{q}}_F+\boldsymbol{C}_F(\boldsymbol{q}_F,\dot{\boldsymbol{q}}_F)\dot{\boldsymbol{q}}_F+\boldsymbol{g}_F(\boldsymbol{q}_F)=\boldsymbol{\tau}_F-\boldsymbol{J}_C^T\boldsymbol{\lambda} \quad (2)$$

where suffixes O and F indicate the object and finger, respectively; $\boldsymbol{r}_O$ is the position and orientation of the object; $\boldsymbol{v}_O$ is the velocity of the object; $\boldsymbol{q}_F$ is the finger joint angle; $\boldsymbol{\tau}_F$ is the finger joint torque; $\boldsymbol{M}$ is a symmetric and positive inertia matrix; $\boldsymbol{Cv}$ is a quadratic velocity term including the Coriolis force and centrifugal force; $\boldsymbol{g}$ is a gravitational term; and $\boldsymbol{J}_C$ is the kinematic Jacobian of the hand. $\boldsymbol{\lambda}$ is the undetermined multiplier in Lagrange's equation. Eq. (1) is the equation of motion of the target object. Meanwhile, Eq. (2) is the equation of motion of the finger. When the robot hand grasps the object as shown in **Fig. 3**, the constraint of the grasp is given by

$$\boldsymbol{G}_C^T\boldsymbol{v}_O=\boldsymbol{J}_C\dot{\boldsymbol{q}}_F \quad (3)$$

where $\boldsymbol{G}_C$ is called the grasp mapping. According to the assumption that $\boldsymbol{J}_C$ is nonsingular, we get

$$\begin{aligned}&\boldsymbol{M}_O(\boldsymbol{r}_O)\dot{\boldsymbol{v}}_O+\boldsymbol{C}_O(\boldsymbol{r}_O,\dot{\boldsymbol{r}}_O)\boldsymbol{v}_O+\boldsymbol{g}_O(\boldsymbol{r}_O)\\&\quad+\boldsymbol{G}_C\boldsymbol{J}_C^{-T}(\boldsymbol{M}_F\ddot{\boldsymbol{q}}_F+\boldsymbol{C}_F(\boldsymbol{q}_F,\dot{\boldsymbol{q}}_F)\dot{\boldsymbol{q}}_F+\boldsymbol{g}_F(\boldsymbol{q}_F))\\&\quad=\boldsymbol{G}_C\boldsymbol{J}_C^{-T}. \quad (4)\end{aligned}$$

Equation (4) is a dynamics model in which the constraints are not represented explicitly.

3.2. Robot Hand Control

The cooperative control of multiple fingers on a robotic hand used to perform an operation by grasping a target object is a basic technique of dexterous manipulation. For many cooperative controls, widely used control laws are based on compliance control [16], impedance control [17], control of underactuated hands [18], and dynamic control [19] together with position and force laws based on hybrid control [20]. In these control laws, it is assumed that the dynamics of the system control are known.

However, it is often difficult to find the exact dynamics of a system. In addition, the dynamic parameters of the system will vary depending on the object being manipulated. Cooperative control using a neural network [21], learning control [22], control without object sensing [23], adaptive sliding control [24], adaptive coordinated control with sliding contact [25], adaptive coordinated control without using a force sensor [26], and adaptive coordinated control with rolling contact [27] have been proposed to accommodate cases where the model parameters of the system are either unknown or fluctuating. As another approach to grasping unknown objects, an unknown object-grasping strategy imitating the human grasping reflex [28] has been presented.

4. Application of Robot Hands

Humanoid robot hands are used not only in humanoid robots but also various applications such as multifingered haptic interfaces [29], electromyogram prosthetic hands [30], hand rehabilitation support systems [31], robotic measurement systems for breast engorgement [32], breast cancer palpation training systems [33], and educational training systems for hand rehabilitation [34]. Research into these applications is introduced briefly.

4.1. Multifingered Haptic Interface

Haptic interfaces are used to present force and tactile feeling to humans in cases of telecontrol for robots, manipulating objects in a virtual reality (VR) environment, playing games with force feeling, and so on. Some of these interfaces provide three-dimensional (3D) force feelings to the human fingertips, and a few haptic interfaces cover the workspace of the human arm.

Over the last three decades, haptic interfaces that present force and tactile feelings to the fingertips of humans have been investigated extensively. Some of these interfaces [35, 36] provide three-dimensional (3D) force feelings to the human fingertip, and a few haptic interfaces cover the workspace of the human arm.

Haptic interfaces are classified into two types: wearable-type interfaces [36, 37], which are mounted firmly on the human hand, and grounded-type interfaces, which are located on the ground. The wearable-type haptic interface has a large workspace, but with this interface, it is difficult to present three-directional forces or to simulate the weight of virtual objects on the fingertips because the hand mechanism is mounted on the back of the human hand and the exerted force is only one-directional.

By contrast, the grounded-type haptic interface generally has a fairly small workspace compared with the wearable-type haptic interface, but a grounded-type haptic interface consisting of an arm and fingertips [35] can be used in a large workspace. A haptic interface must be safe, function in a wide operation space, and represent the weight of virtual objects as well as the force at the contact points. In addition, it should not produce an oppressive feeling when attached to a person, and it should not represent its own weight.

Fig. 4. Multifingered haptic interface robot HIRO III.

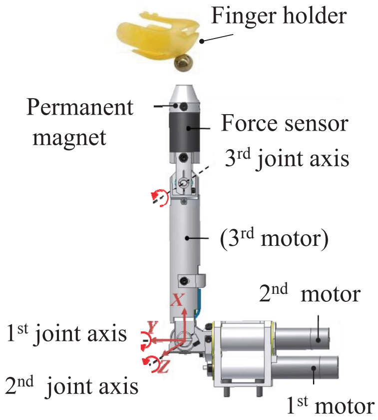


Fig. 5. Mechanical structure of haptic finger.

4.1.1. Mechanical Structure of HIRO Hand

Multifingered haptic interfaces joined to the arm can provide a wide operation space. However, most of these interface systems are mounted on the back of the human hand. Fixing the haptic interface to the hand can give the operator an oppressive feeling since the interface must be firmly bound. To reduce this oppressive feeling and increase safety, we developed multifingered haptic interface robots that are located opposite to the human hand, including the HIRO [38], HIRO II+ [39], and HIRO III [40] (see **Fig. 4**). The HIRO III can present 3D forces to the operator's five fingertips.

The HIRO consists of an interface arm, a haptic hand with five haptic fingers, and a controller; it can present a three-directional force at each of the five fingertips. The mechanical structure of the haptic finger of HIRO III is shown in **Fig. 5**. It has three joints, allowing for three DOFs. The first joint, relative to the hand base, allows for abduction/adduction. The second and third joints allow for flexion/extension. The finger layout of the haptic hand is designed to maximize the volume formed by the intersecting workspaces of the haptic and human fingers.

To read the loading of the fingers, a three-axis force sensor was installed in the second link of each haptic finger. To manipulate the haptic interface, the user wears a finger holder on his/her fingertips. This finger holder has an iron sphere that forms a passive spherical joint when attached to the permanent magnet at the force sensor tip. The passive spherical joint has two roles. The first is to adjust for differences between the orientation of the human and haptic fingers. Each human finger has six DOFs, while each haptic finger has only three DOFs. Hence, an additional passive three DOFs are needed. The second role of the spherical joint is to ensure that the operator can remove his/her fingers from the haptic interface in case of malfunction. The suction force by the permanent magnet is 4.3 N. The maximum output force at a fingertip is 3.6 N.

4.1.2. Control of Haptic Interface

The HIRO III is a redundant interface robot with 21 DOFs. When five human fingertips are connected to the HIRO III through the passive spherical joints, the haptic hand posture is nonunique because of the redundancy of HIRO III. To take this redundancy into account, redundant force control and hand-manipulability-based control were developed. This control method combines finger force control and arm position control. Each finger is controlled independently by a proportional-integral (PI) force control using a force error at the fingertips. In arm position control, a desired hand posture is determined to maximize the hand manipulability measure in order to respond to an operator's various hand poses. The hand manipulability measure having k fingers is defined as follows:

$$PI = \sum_{i=1}^{k} (\alpha_i W_i + \beta_i P_i) + Q \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

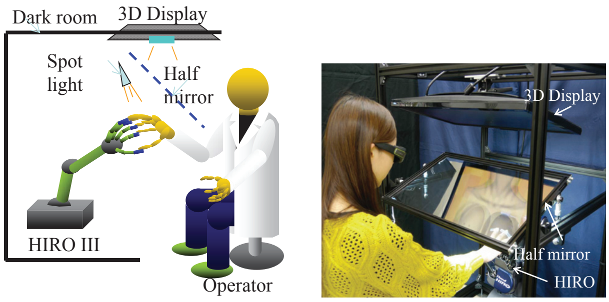
where α_i and β_i are weighting coefficients, and W_i is a manipulability measure of the i-th haptic finger given by $W_i = \sqrt{\det(\boldsymbol{J}_{F_i}^T \boldsymbol{J}_{F_i})}$, where $\boldsymbol{J}_{F_i}$ is a kinematic Jacobian of the i-th haptic finger. P_i is a penalty function of the i-th haptic finger to keep the joint angle within the range of movement, and Q is a penalty function to prevent a large arm motion, which sometimes confuses the operator because it creates the illusion that the device is malfunctioning. When the operator moves his/her hand, HIRO follows the motion of the operator's fingers and represents the force's feelings.

4.1.3. Application Systems Using HIRO

The use of multifingered haptic interfaces has contributed to the development of novel application systems including the Future Haptic Science Encyclopedia [41]. Some applied systems mainly in the medical field are introduced below:

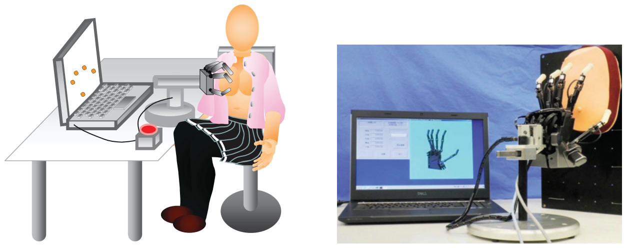
(1) Breast palpation training system [42]

Training environments for breast cancer palpation that are easily accessible by medical users have been greatly in demand, reflecting the increasing number of breast cancer patients. A virtual human breast model utilizing virtual reality (VR) technologies can completely eliminate the need for real human patients in experiments. The haptics are rendered for each finger individually by HIRO, and the graphics are rendered by a 3D display system with a half mirror, as shown in **Fig. 6**. The simulator is based on the Finite Element Method (FEM) with a corotational formulation.



(a) System composition (b) Developed system

Fig. 6. Breast cancer palpation training system.



(a) System concept (b) Prototype of measurement system

Fig. 7. Measurement system for breast engorgement.

(2) Measurement system for breast engorgement [32]

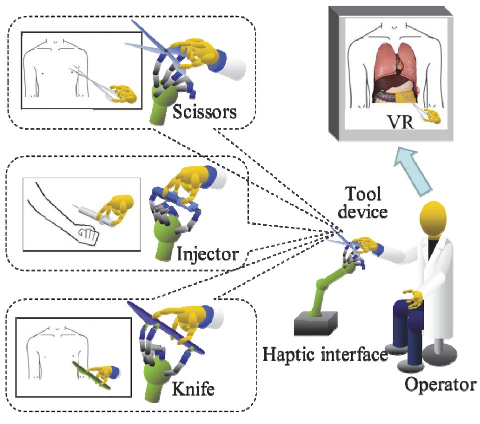
Breast engorgement, a potentially harmful condition among new mothers, is difficult to quantify objectively. We proposed a tabletop system, as shown in **Fig. 7**, that can precisely quantify breast stiffness as an estimate of engorgement. The system uses a HIRO that can simultaneously measure the fingertip force and position with high precision at multiple points.

(3) Surgery training system using plural devices [43]

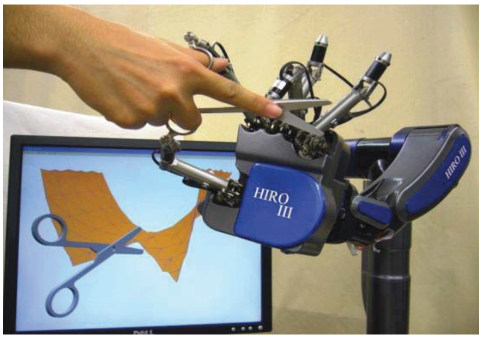
Tool-type haptic interfaces such as scissors are used to present force feeling for surgical training in VR environments. A presentation of force feelings of plural tools requires many single tool-type haptic interfaces. A training system for plural surgical devices, as shown in **Fig. 8**, has a greater potential for the force feelings than a single tool-type training system with regard to the workspace and removable equipment.

(4) Skill transfer system [44]

One important use of the haptic interface is in virtual training systems for expert skill transfer from a trainer to a trainee in medical fields, industries, and others. To transfer skills involving such fine motor tasks, instruction on how to move the fingers and use fingertip forces is essential. A haptic training system

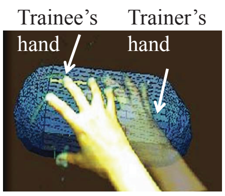


(a) Concept of plural surgical tool devices

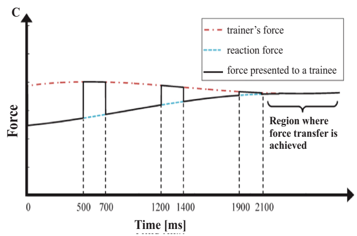


(b) HIRO connected to a medical scissors-type device

Fig. 8. Training system for surgical tool devices.



(a) Hand motion image



(b) Displayed force

Fig. 9. Skill transfer system using virtual trainer's hand.

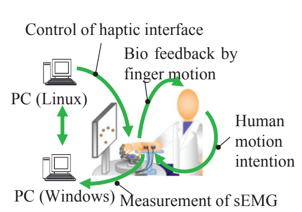
for fine motor skills using HIRO, as shown in **Fig. 9**, was developed. The force presented to a trainee is alternately trainer's force and trainee's force.

(5) Finger rehabilitation support system [45]

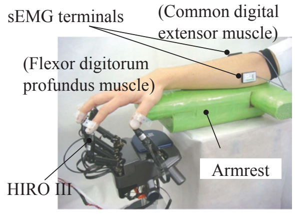
A surface electromyogram (sEMG) records the electrical activity of muscles underlying the skin and is useful for rehabilitative robotic devices. A finger rehabilitation support system using HIRO, as shown in **Fig. 10**, was researched. Finger motion is generated by biofeedback. This system will be effective for patients with peripheral nerve injuries to the arm.

(6) Virtual robot teaching system [46]

A virtual robot teaching system consisting of human demonstration and motion-intention analysis in a virtual reality environment using HIRO has been presented, as shown in **Fig. 11**. The position and orientation of the robot hand were determined to maximize the robot hand's manipulability. In the motion-intension analysis, human motion data consisting of contact points, 3D grasp forces, and hand and object positions are segmented into plural primitive motions, and the type of task was analyzed based on the sequence of the primitive motions. Based on the motion intention analysis, a series of robot commands are generated for the object coordinate frame.



(a) Outline of bio feedback system



(b) System setup

Fig. 10. Biofeedback hand rehabilitation support system.

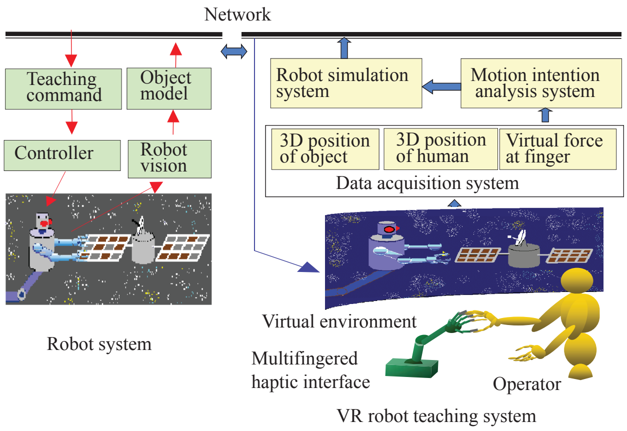
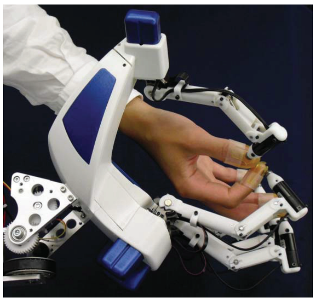


Fig. 11. Conceptual figure of virtual robot teaching.

4.1.4. New Design of Haptic Interface

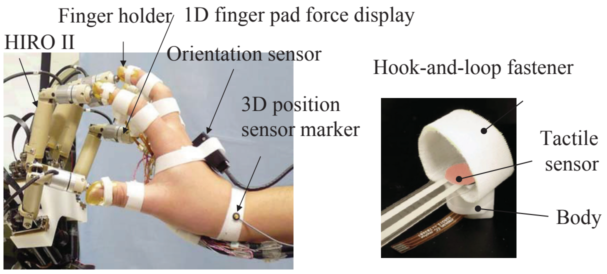
In performing activities in our daily lives, we easily manipulate objects with both the left and right hands. We also frequently handle small objects such as the handgrip of a cup or pencil. A bimanual haptic interface system using two HIRO IIIs is restrictive for the user's hand position because the HIRO IIIs are front-faced types. To solve this problem, a multifingered haptic interface located on the side face of the user's hand and arm was developed [47], as shown in **Fig. 12**. The arm is grounded without causing interference to the human body, and the haptic hand is placed on the back of the user's hand so that only the user's fingertip is connected to the interface fingertip through a fingertip holder. This is called a side-faced-type multifingered haptic interface (SF-HIRO). This haptic interface allows the user to grasp small objects and achieve bimanual manipulation in a virtual reality environment.

(a) Developed system



(b) Connection between human hand and interface

Fig. 12. Side-faced multi-fingered haptic interface, SF-HIRO.



(a) Developed system (b) 1D finger pad force display

Fig. 13. Prototype of hand haptic interface.

Humans manipulate objects using force and tactile feelings on their fingertips, finger pads, and palms. For example, medical doctors search for tumors during a breast palpation and manipulate internal organs during surgery using not only their fingertips but also their finger pads and palms. To allow doctors to practice such medical procedures in a virtual environment, a hand haptic interface that can apply forces to not only the fingertips but also the finger pads and palms is desired. The density of tactile sense organs in the human finger [48] is high on the fingertip and low on the finger pad. Hence, the human finger has high sensitivity with regard to force on the fingertip but low sensitivity on the finger pad and palm. This suggests that a hand haptic interface that consists of 1D force display devices and a 3D fingertip force display device would be effective for use in a virtual environment. **Fig. 13** shows a prototype of the hand haptic interface [49].

To gain skills such as palpation through such a virtual training system, a haptic interface that can present the sensation felt when a human touches soft, yielding objects such as human flesh is required. To display the feeling of softness at the fingers using both kinesthetic and cutaneous information, a haptic interface that connects a new finger holder by installing a tension-controllable flexible sheet into the finger holder [50] was developed.

4.1.5. Human Perception Using Haptic Interface

There have been many reports of human perception at the fingertips with regard to the force magnitude [51], force direction [52], magnitude and direction [53, 54], edge sharpness perception [55], and multipoint force perception [56]. Most of these studies focused only on force perception at the fingertip. Research on the biomechanics of the finger pad [57] is useful in the design of a finger pad force display, but wearable finger-pad force display devices may actually reduce the force sensitivity of the human finger because they must be firmly fixed to the finger with a belt or loop fastener. Therefore, reducing the size of the finger-pad force display device and developing a wearable method of plural finger-pad force display devices for the human hand will have an effect on force discrimination.

4.2. Electromyogram Prosthetic Hands

Electromyogram prosthetic hands [58, 59] with actuators to realize multidegree operationality and controlled by a user's sEMG are necessary to maintain the quality of life for forearm/hand amputees. This is one of the applications for robot hands. It is important that the prosthetic hand be light and unitized because amputees usually feel uncomfortable if the hand feels massive, and a unitized prosthetic hand is easy to apply and maintain. Moreover, the hand should have a grasping force that will allow an amputee to manipulate objects encountered in daily life such as plastic bottles, cups, and plates. It is also desirable for the hand to have many DOFs for dexterous manipulation. In particular, both wrist motion and finger motion are required because coordinated motion between the fingers and wrist is necessary for tasks such as opening doors or writing letters. Wrist motion can facilitate various types of object handling.

To satisfy these needs, an sEMG prosthetic hand with a grasping strategy consisting of thumb opposition with a high grasping force was developed [60].

4.2.1. Mechanical Design

The prosthetic hands shown in **Fig. 14** were designed to satisfy the following specifications: a thumb with three joints and two DOFs for extension/flexion and opposition motion, four fingers with three joints and one DOF for flexion/extension, a wrist with two DOFs for pronation/supination and dorsal/palmar motion, a total mass of 300 g or less, a gripping force of 20 N or more, all motors and a field programmable gate array (FPGA) control circuit mounted in the hand frame, and a size similar to that of the hand of a Japanese adult female.

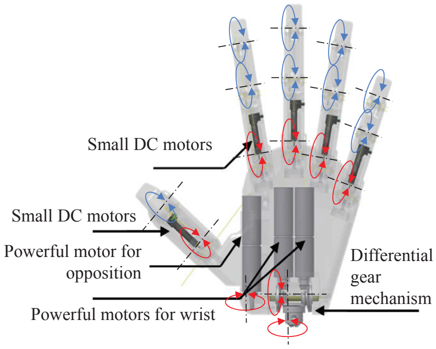


Fig. 14. Design of prosthetic hand.

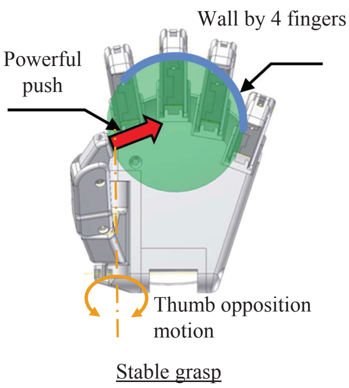


Fig. 15. Grasping strategy.

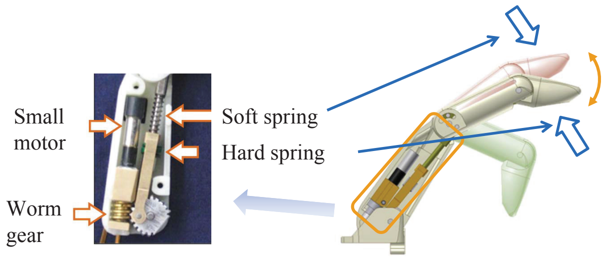


Fig. 16. Passive mechanism of finger.

Fig. 17. Grasping various types of objects with artificial skin. From left: tennis ball, plastic bottle, screw nut, and key.

Powerful motors are necessary for realizing strong grasp forces; however, generally, this type of motor is too heavy to employ for each finger. Therefore, a novel grasping strategy was invented in which the four fingers maintained a resting state without back motion while the thumb pushed the object to a virtual wall constructed by the four fingers (see **Fig. 15**). To realize the grasping strategy, a worm gear system without back-drivability was used as a reduction gear mechanism. By adopting this mechanism, the fingers could maintain their resting state even if external forces were applied, and therefore the hand could use small motors for finger flexion/extension. Only the thumb motor had high power. This was effective for high grasping forces and light mass. In addition, the mechanism without back-drivability was effective in saving electrical energy, which is important in a prosthetic hand system.

It was possible, however, that this mechanism would result in a stiff or hard grasp. To deal with this grasp issue, a passive flexion/extension mechanism, as shown in **Fig. 16**, was added to the link mechanism. The passive mechanism had a link rod with two types of spring (soft and hard). The hard spring worked when external forces were applied at the fingertip along the "extension direction." The finger could closely fit the frame of the object by this hard spring. This supported the hand in grasping a target object with all fingers. The soft spring worked when external forces were applied along the "flexion direction." If the finger hit an obstacle, the finger could absorb the shock and work as a safety mechanism. The palm of the prosthetic hand was equipped with an FPGA control circuit system. The developed prosthetic hand can grasp various objects, as shown in **Fig. 17**. The hand is covered with artificial skin.

4.2.2. Control by sEMG and Voice

In daily life, humans make combination motions with their fingers and wrist joints. For example, the use of a key to lock or unlock a door requires a side grasp with the thumb and index finger and wrist pronation or supination motion. Therefore, the possibility of key operation by sEMG was examined as an experimental target task using a neural network (NN) system [61]. Pattern recognition of the hand and finger state from an sEMG may be able to function as a computer interface. The possible number of patterns to be recognized is limited. However, to operate a multifingered robot hand according to the operator's intent, it is more important to estimate the finger joint angles than to determine the finger motion patterns. A system that estimates finger joint angles is able to recognize every hand state, and therefore has high general versatility.

Instead of using a pattern recognition approach, finger joint angles from an sEMG were estimated using an NN with a recurrent structure. In this research, an NN was used to estimate a total of five joint angles (the metacarpophalangeal (MP) joint angles of five fingers) from the sEMG during the individual movement of each joint. The root mean square (RMS) of the estimation error was $\sim$11%.

As another approach to prosthetic hand control, the use of speech can enhance the reliability and ability of hand operation [62, 63] because speech signals are relatively unaffected by the operator's biological condition. Speech operations, however, can be noisy for those around the operator and are not a good command source during eating or talking. Current prosthetic hand controls are forced to use only one biosignal-based control. A mixed approach of speech and sEMG, better able to respond to the operator's biological conditions and environment, will enhance the reliability and usability of prosthetic hand control.

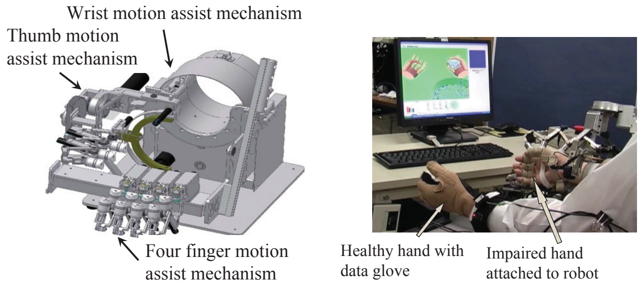
4.3. Hand Rehabilitation Support System

A stroke occurs when the blood supply to the brain is blocked or when a blood vessel in the brain bursts. In this case, the patient needs timely and persistent rehabilitation to recover his or her lost abilities and to regain a normal daily life. It is understood that an earlier start to rehabilitation contributes to regaining lost abilities and skills. In particular, rehabilitation in the acute stage and convalescence stage has a significant effect of preventing disuse muscle atrophy. Long rehabilitation training sessions with therapists, who are in relative shortage, however, are not always possible for patients to obtain. A solution to this problem is a rehabilitation support system that allows the patient to carry out rehabilitation exercises by himself or herself. We call this patient self-controlled rehabilitation therapy. Most disabilities caused by cerebrovascular accidents (CVAs) are hemiplegic; that is, only one side is impaired. Arm rehabilitation therapy with the aid of a robot [64] that involves bimanual, mirror-image, and patient-controlled therapeutic exercises is one type of self-controlled rehabilitation.

On the other hand, hand rehabilitation is somewhat difficult because the hand possesses many degrees of freedom of motion, and a hand-motion assist device that can be attached is small in size. Research on the function of the fingers by electrical stimulation [65], hand rehabilitation devices [66, 67], virtual reality-based stroke rehabilitation [68], and telerehabilitation [69] have been presented. To enhance the quality of life of patients with hand impairments, rehabilitation therapy for the manipulation function and fine motions such as turning knobs or handling chopsticks is needed [70].

In hand rehabilitation, a robotic device is required to assist not only the flexion/extension but also the abduction/adduction motions of each joint of the fingers and thumb independently. Another major requirement for such a device is to assist the motion of thumb opposition because the dexterous manipulation of objects by humans requires thumb opposability. Moreover, the palmar flexion/dorsiflexion of the wrist and the pronation/supination of the forearm have important roles in manipulation functions and fine motions [71]. Furthermore, rehabilitation support systems are required to have a function to enhance and maintain a patient's motivation for long-term rehabilitation because rehabilitation is often accompanied by pain and boredom.

The hand rehabilitation support system [72, 73] shown in **Fig. 18** assists disabled persons in pursuing a course of rehabilitation on their own in order to regain lost functions as soon as possible. The patient can train for hand rehabilitation by enjoying the virtual training system, which



(a) Mechanism (b) User interface

Fig. 18. Hand rehabilitation support system.

consists of pouring water, playing the piano, the game of paper-rock-scissors, and so on, by himself/herself. The robot system was developed for self-controlled rehabilitation therapy by patients and supports not only the flexion/extension and abduction/adduction motions of each joint in the hand but also thumb opposability. The affected hand is controlled by the motion command from the other unaffected hand in order to produce bilaterally symmetrical motions. The self-controlled rehabilitation strategy is efficient because the user can exercise by thinking the training motion through the unaffected movement. This system has been evaluated in a hospital.

4.4. Telemanipulation System

A haptic telemanipulation system is a dual-robot system in which a remote slave robot is controlled to follow the master haptic interface robot, which is operated by a human operator. This system can be applied not only in dangerous environments such as space [74], nuclear reactors, and deep-sea conditions but also in service environments such as telesurgery [75], telerehabilitation [76, 77], biomanipulation [78], and the daily life care of aged persons [79]. Haptic sensations are a crucial factor in many tasks. These tasks are successfully achieved if the haptic device effectively simulates the haptic sensations of real contacts and manipulation. This is accomplished by a bilateral control scheme.

Many control methods have been proposed [80]. Several control methods can cope with uncertainties, time delays in telecommunication [81], parameter estimations of the environment of the slave side [82], and the nonlinearity of robot dynamics [83]. Experimental results of robot arms and multifingered robot hands have been presented [84, 85].

A multifingered haptic interface is required for the telemanipulation of a multifingered hand robot [86, 87]. Most of these haptic interfaces present only the contact force around the flexion/extension axis of the finger using an exoskeletal mechanism. It is important to control both the hand and arm in order to expand the workspace. To extend the workspace, a telemanipulation control with a communication time delay for humanoid hand robots using HIRO III [88], as shown in **Fig. 19**, was developed. The slave robot was a humanoid hand robot using a modified

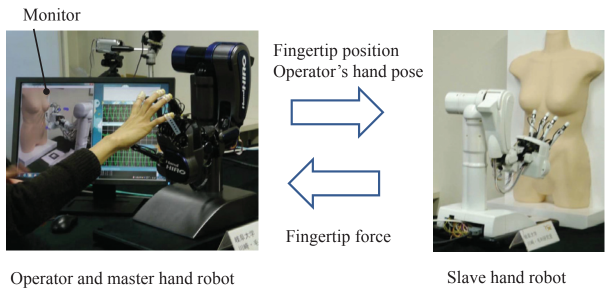


Fig. 19. Telepalpation system.

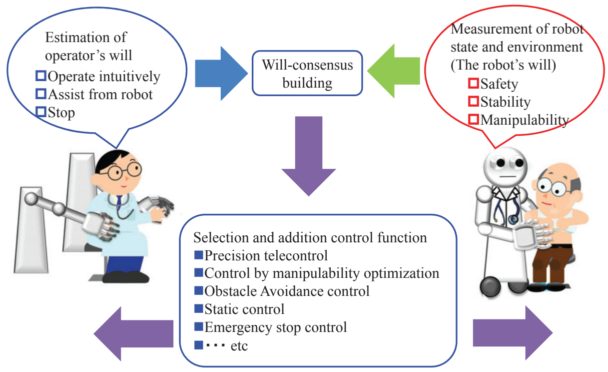


Fig. 20. Concept of will-consensus building.

HIRO III whose fingertip shape was modified like a robot hand for object manipulation. In the master, the hand was force-controlled and the arm was position-controlled based on a hand manipulability index. In the slave, the hand was position-controlled to follow the master's fingertip position, and the arm was position-controlled based on a hand manipulability index that was the same as that of the master arm control. This telemanipulation system was applied in a telepalpation system [89]. This led to the proposal of a method for visualizing the stiffness of a soft object for a palpation support information system by a teleoperated robot hand.

The stiffness of the contact area between a soft object and the robot finger was estimated by a recursive least-squares method with a forgetting factor using an impedance dynamics model. Using the estimated stiffness and direction of the contact force, a scalar parameter for the visualization of stiffness was estimated.

Clearly, any robot that will contact a human requires strict safety management. Hence, a safety control method is very important for the palpation system. We previously proposed a telecontrol method based on will-consensus building [89]. In this method, the magnitude of the contact force was monitored. If the magnitude exceeded the threshold value, the robot stopped at the software level. The robot also stopped under other conditions, for example, for voice input from the patient. However, as there could be cases where the doctor wants to push at a force greater than the limited value, we designed the system so that the doctor could continue to operate the slave robot via the master robot by inputting a voice command. The process flow is shown in **Fig. 20**. In the proposed system, moreover, both the system and the doctor make judgmental decisions. Therefore, the system remains safe even if one of them is incorrect.

5. Conclusion

The dynamics and control of humanoid robot hands are almost established, and many applications using humanoid robot hands are expected. However, there remain many issues such as compactness, high-output power of the mechanism, highly reliable tactile sensors, teaching of the humanoid hand robot, and artificial skills to manipulate the object in a dexterous manner. We are in the hope that the study of humanoid robot hand is to contribute significantly in the industry and society.

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- "Perception and Haptic rendering of Friction Moments," IEEE Trans. on Haptics, Vol.4, No.1, pp. 28-38, 2011.

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Membership in Academic Societies:

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- The Robotics Society of Japan (RSJ)
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