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Development of an anthropomorphic robot hand and wrist for teleoperation applications

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***Abstract*—In this work, we are developing an anthropomorphic robot hand and wrist to be teleoperated by a human using a glove input device. The present model of the hand is intended for use in grasping operations, and consists of a palm, two fingers, an opposed thumb, and two wrist joints that provide pitch and roll movements. Each of the three digits of the robot hand has two pitch joints to enable flexion and extension, and incorporates a new passive switching mechanism that allows a single actuator to drive the two joints successively. The hand/wrist system has a total of five independent degrees-of-freedom. It is driven by five remotely located DC motors through servo control, and the drive from the motors is transmitted to the hand and wrist joints through flexible sheathed cables acting as tendons. The work focuses on replicating as closely as possible the shape, size, natural motions and applied forces of the human appendage, while keeping the complexity of the robot hand and wrist to a minimum. The first prototype of the hand has been demonstrated, and is capable of holding a wide variety of objects of different shapes and sizes using both precision-type and power-type grasp configurations.**

I. Introduction

THE development of versatile and dexterous robot hands has been an important activity in various research institutions worldwide for more than twenty years. The main academic motivation for this research activity is to study and analyze robotic grasping and manipulation, with the long-term goal of improving the state of the art in artificial manual dexterity. In some cases, this general area of research has also been instigated by a number of industrial motivating factors. These include the need for increased flexibility in manufacturing [1], [2], requirements for space exploration [3], [4]. and the development of prosthetic devices for amputees [5], [6].

A class of target applications of robot hands that is rather under-represented, at least as a primary motivator for research in the area, is that of teleoperation applications. While many of the robot hands in the literature can be adapted into teleoperated devices if required, only a relatively small number of robot hands have been specifically designed and developed from the outset to be controlled through teleoperation (e.g. [7], [8]). This is somewhat surprising, given the wealth of useful applications for such devices, such as the handling/disposal of hazardous materials including bombs and radioactive substances; the exploration of hazardous areas and/or of areas inaccessible by humans; the handling of very large/heavy or of very small/delicate objects; and the remote transfer of manual expertise and dexterity.

In this work, our objective is to develop an anthropomorphic robot hand and wrist system that is intended specifically for teleoperation and, ultimately, for telepresence applications. Our work focuses on the development of a system that can be controlled by a human operator wearing a glove input device, and to this end our emphasis has been directed towards replicating as closely as possible the natural features and properties of the human hand. In particular, importance was given to the ranges of motion and force capabilities of the fingers, as well as to the overall size and shape of the hand. To supplement the design of the robot hand, we have carried out a number of dedicated experiments to measure typical values and ranges of human fingertip forces during grasping. At the design stage, emphasis has also been placed on the minimization of complexity and cost of the robot hand, while still achieving the primary objectives of the first prototype.

II. Basic Design Requirements

Designs of robot hands that are intended to imitate the human counterpart in form and/or function, are often based on targeted studies of the characteristics and performance of the human hand (see for example [9]). In our work, we were concerned with the development of a teleoperated robot hand that would be able to carry out human-scale activities, and that would be capable of conveying a sense of remote presence to the human operator. It was therefore important for the robot hand to be similar in size and shape to the human hand, and to be capable of applying human-scale forces when grasping objects of different size, shape, and weight. It was also important for the robot hand to be able to replicate a number of finger postures and grasp configurations that are commonly used by humans to handle various objects.

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During the conceptual design stage, we sought to determine the number of human grasp postures that would be reproducible by the robot hand by referring to the taxonomy of human grasps constructed in [10]. In the case of *precision-type* grasps, where the object makes contact with two or more fingertips (but not with the palm), we required the robot hand to be capable of reproducing prismatic-type grasps, with the thumb opposing one or more fingers, as well as circular-type grasps, with the thumb and two or more fingers contacting the object in radial symmetry. In the case of *power-type* grasps, where the object is held by the fingers against the palm, we also required the robot hand to be capable of reproducing both circular-type grasps (to constrain spherical objects) and prismatic-type grasps (to constrain elongated objects).

With regard to actuation of the hand and wrist joints, we required a fast, real-time response to the movements of the master device in order to facilitate handling of the remote object by the human operator. The ranges of motion of the finger, thumb and wrist joints were required to be as close as possible to those of the human counterparts.

To determine the force requirements of the robot hand, as well as the required number of digits, we carried out a number of dedicated human grasping experiments, as described in section III below.

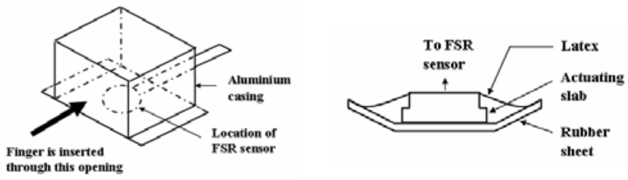
III. Experimental Determination of Human Grasping Forces

A. Objective of the Experiments

The robot hand was required to have the capability of applying forces on the grasped object that were equal to the equivalent forces that could be applied by a typical human. To determine these maximum force requirements, we carried out a number of tests to measure typical values and ranges of human fingertip forces during standard precision-type grasping and picking operations. These tests utilized a set of force sensing devices, developed specifically for this application, which could be worn over the human fingertips during grasping. The experiments were carried out using objects of different shapes and weights, using both circular-type and prismatic-type precision grasp postures, and using two, three, and four finger contacts. The results of the experiments also gave us an insight on the minimum number of digits required by the robot hand to achieve effective grasping of the set of objects under consideration.

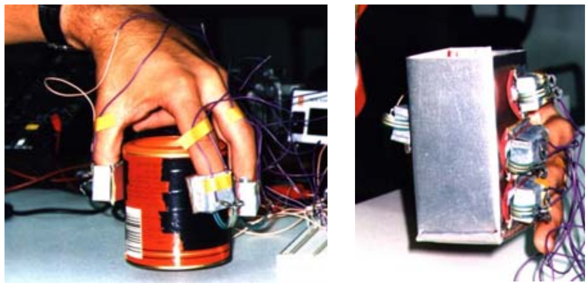
B. Apparatus and Procedure

The sensors that were used to measure the human fingertip forces during the experiments were force sensing resistors (FSRs) made of polymer thick film (PTF) [11]. These sensors are very thin and have negligible weight. They exhibit a decrease in resistance with an increase in the force applied to the effective surface area of the sensor. The force sensing assembly is illustrated in Fig. 1. Each device



(a) (b)

Fig. 1. Force sensing device worn during the human grasping experiments, (a) casing, (b) rubber surface and actuating slab.



(a) (b)

Fig. 2. (a) Experimental set-up for grasping and picking up (a) a cylindrical object from the top, using four finger contacts, (b) a rectangular object from the side, using four finger contacts.

consisted of an aluminum casing into which the finger could be inserted. One wall of the casing was replaced by a rubber sheet, stretched over an aluminum part of cylindrical cross-section (the actuating slab) that had an area that matched the active area of the FSR. The actuating slab was kept in place by means of a stretched latex sheet as shown. The device could be worn over the finger during grasping, such that the rubber surface made contact with the grasped object, and the finger contact force was transmitted through the actuating slab to the FSR. The FSR sensors have an accuracy of about ±10%, which was sufficient for our application. The sensor readings also tend to be temperature dependent, however this was not a problem in our application since the FSR was in very close proximity to the human finger, and therefore was kept at a constant temperature throughout all the experiments. The devices were calibrated prior to the experiments.

Two sets of experiments were carried out. In the first set, a cylindrical container was lifted and held from the top in a circular-type precision grasp as shown in Fig. 2 (a), while in the second set a rectangular container was lifted and held from the side in a prismatic-type precision grasp as shown in Fig. 2 (b). Each of the two sets consisted of separate experiments using four fingers (thumb, index, middle, and ring), three fingers (thumb, middle, and ring) and two fingers (thumb and middle). In each individual experiment the weight of the container was increased in increments of approximately 1 N, and the FSR readings were recorded for every value of the weight. Weights were increased until the human subject was unable to apply sufficient force to hold

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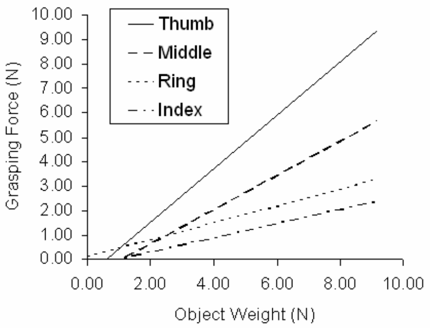


Fig. 3. Grasping forces applied by the index, middle, and ring fingers and by the thumb, as a function of weight of the object, to hold a cylindrical object from the top using four finger contacts (see Fig. 2(a)).

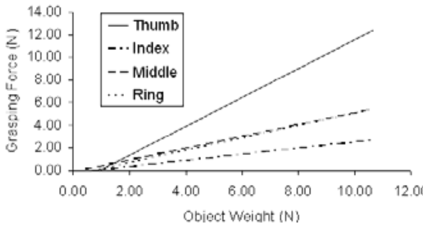


Fig. 4. Grasping forces applied by the index, middle, and ring fingers and by the thumb, as a function of weight of the object, to hold a rectangular object from the side using four finger contacts (see Fig. 2(b)).

the object and the grasp became unstable. All results were taken as an average over three readings, and all readings were taken after the force sensing device had been worn for a few minutes to allow the FSRs to reach a consistent temperature. In all cases, the human subject applied grasping forces that were judged to be the minimum necessary to keep the object from slipping.

C. *Results*

The results for the two configurations of four-finger experiments are shown in Fig. 3 and Fig. 4 respectively. As can be seen from the figures, the thumb consistently applied the greatest force, even in the case of the circular-type grasp. In both cases, a somewhat surprising result was that, among the fingers under consideration (i.e. excluding the little finger), the index finger provided the least force during grasping. Our explanation for this is based on the fact that in the human hand the thumb moves in direct opposition to the middle and ring fingers, rather than to the index finger. In precision grasps of objects of the sizes under consideration, and in which the objective is to maintain a secure grasp rather than to manipulate the object, this results in a greater and therefore more important contribution by the middle and ring fingers in comparison to the index finger.

The results for the three and two finger grasping experiments are shown in Figs. 5 to 8. It is to be noted that, while care was taken to maximize the accuracy of the

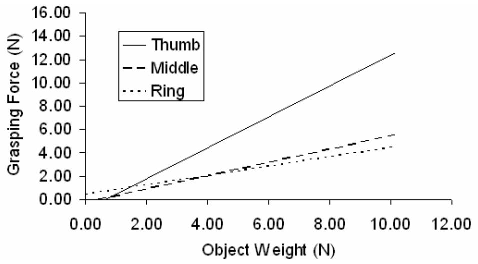


Fig. 5. Experimental results for grasping and picking up a cylindrical object from the top, using three finger contacts.

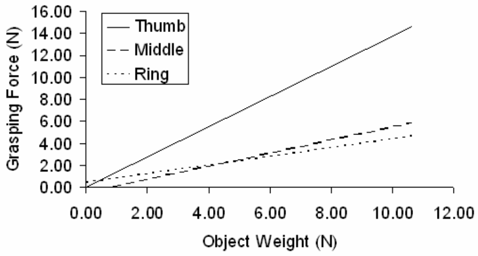


Fig. 6. Experimental results for grasping and picking up a rectangular object from the side, using three finger contacts.

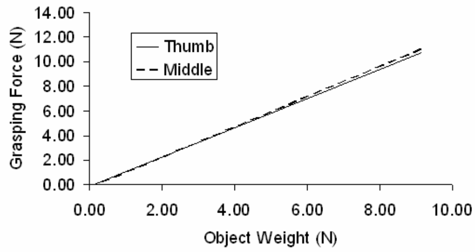


Fig. 7. Experimental results for grasping and picking up a cylindrical object from the top, using two finger contacts.

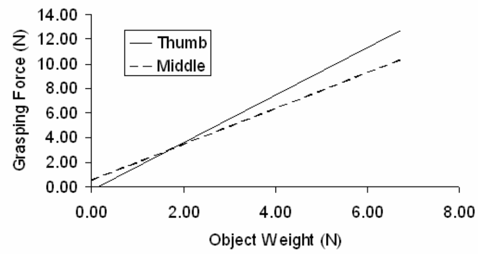


Fig. 8. Experimental results for grasping and picking up a rectangular object from the side, using two finger contacts.

results, the experiments were subject to a number of inherent sources of error. In particular, the force sensing devices deprived the wearer from using his sense of touch to judge when the object was about to slip out of the grasp. This problem was minimized by subjecting the wearer to a long learning and practicing procedure with the devices prior to carrying out the actual experiments. Another problem was the inherent inaccuracy of the FSRs mentioned

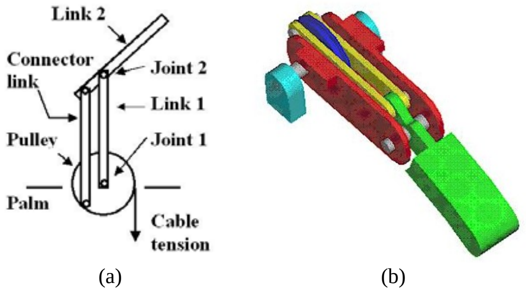


Fig. 9. (a) Kinematic structure of the finger, (b) CAD drawing of the middle finger.

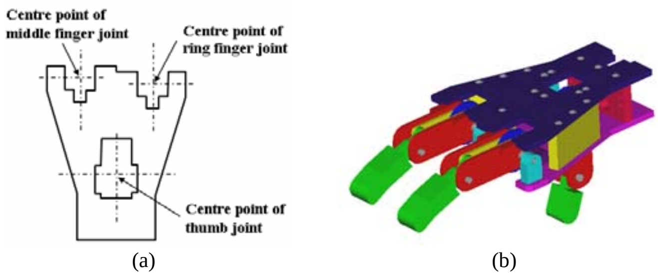


Fig. 10. (a) Drawing of palm plate, showing locations of finger and thumb joints, (b) CAD drawing of the palm and fingers.

previously, however this was deemed acceptable for our application. An advantage of the set-up was that the devices were able to measure only the forces acting normal to the contact area between the finger and the object. This property was very relevant to our application, since we required to measure the *normal* grasping forces required to achieve sufficient *tangential* friction force to hold the objects. In all the experiments, the force sensing devices were oriented such that the rubber surface and actuating slab were normal to the object surface. The static friction coefficient between the rubber surface of the force sensing devices and the surface of the objects was measured separately and was found to be equal to about 0.8.

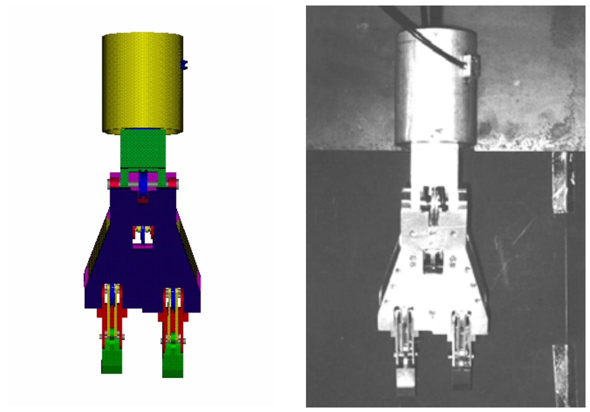
IV. Mechanical Design of the Robot Hand and Wrist

Based on the results obtained in the human grasping experiments, and in order to minimize the complexity of the prototype, it was decided to develop an anthropomorphic robot hand having two fingers, equivalent to the human middle and ring fingers, and an opposed thumb. The hand was designed to lift an object weighing 0.6 kg. The highest fingertip force requirement in the human grasping experiments, to hold a stationary object of this weight with three fingers, was of about 8.1 N (Fig. 6). We applied a factor of 1.5 to allow for upwards accelerations of the object against gravity, and incorporated a further factor of 2 to allow for friction coefficients that could be significantly lower than 0.8 for certain objects. This gave a nominal force requirement for the thumb of about 25 N. As a further safety factor, and to increase the uniformity of the design, the two fingers were designed with the same nominal force requirement as the thumb.

Each digit had two joints, with a linkage structure that was based on the concept shown in Fig. 9(a). The stiffness of the return springs at each of the two joints were set such that upon actuation, joint 1 would move first through its entire range of motion, and this would be followed by movement of joint 2. This mechanism allowed us to use one motor to actuate each finger, but at the same time produced a flexion motion of the finger that was, to a considerable extent, similar to that of the human finger during normal grasping. The anthropomorphism of the two fingers was increased by designing the outermost link to be bent slightly inwards at about two thirds of the way to the fingertip, at a location corresponding to the outermost (third) joint of the human finger. The overall length of each finger, corresponding to the distance between the knuckle and the fingertip in the human hand, was of 115 mm, while that of the thumb was of 100 mm. Cable tensions to achieve the fingertip forces required by the design were of about 180 N. A CAD drawing of the middle finger is shown in Fig. 9(b).

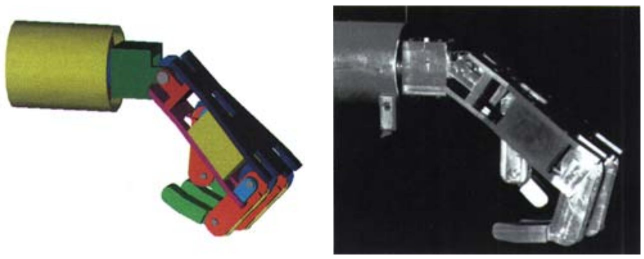
The palm of the robot hand was designed such that the thumb directly opposed the two fingers, and the centerline of the thumb joint was located between the centerlines of the finger joints, so that the digits could not collide. This configuration favoured prismatic-type grasps, however in order to facilitate circular-type grasps of round or spherical objects, the middle and ring fingers were displaced rather than placed in line, as shown in Fig. 10(a). This feature is also found in the human hand. The palm was designed to be roughly equal in size to the human equivalent. A CAD drawing of the palm and digits is shown in Fig. 10(b).

The two degree-of-freedom wrist had a pitch joint that could move through 90^o (-45^o to $+45^o$), and a roll joint that could move through 180^o, with maximum cable tension requirements of 100N and 125N respectively. The joints were designed to support a 600 g object held in any orientation of the hand. The mechanical design of all the sub-assemblies of the system took into account routing of the transmission cables to eliminate coupling of joint motions, as well as the use of tension limiting springs to protect against overloading of the transmission. All of the joints incorporated torsion return springs to move the hand and wrist joints to their natural positions when cable tensions were released. The calculations of all the required cable tensions took into account the torques of these return springs, as well as gravity forces that were dependent on joint positions. The hand and wrist system are shown in Figs. 11 and 12.



(a) (b)

Fig. 11. The robot hand and wrist (plan view), (a) CAD drawing, and (b) photograph.



(a) (b)

Fig. 12. The robot hand and wrist (side view), (a) CAD drawing, and (b) photograph.

V. Drive and Control Systems

The hand/wrist system has a total of five independent degrees-of-freedom. It is actuated using five identical, remotely located, 3-pole DC electric motors with a maximum speed of 19,000 rpm and a working torque of 3.75 Ncm. The drive from the motors is transmitted to the hand and wrist joints through flexible sheathed cables acting as tendons. In order to obtain adequate torques to provide the required cable tensions, gear reduction ratios of 300:1 were used for the fingers and thumb, and ratios of 250:1 were used for the two wrist joints.

Motor control was achieved using a second order servo controller that utilized position feedback information from rotary potentiometers. Due to mechanical constraints the potentiometers were not mounted directly on to the joints of the robot hand, but were instead mounted on the output shafts of the gearboxes. The block diagram representing the control system for each joint is shown in Fig. 13. The reference voltage signal V_i is obtained from a position sensor on the master device. The difference between V_i and the output rotary potentiometer signal V_o constitutes the error signal V_e. In our application an amplified error signal V_f is obtained directly using a differential amplifier, and this voltage drives the DC motor until the angular position θ_o at the output shaft of the gearbox reaches the desired value. In Fig. 13 θ_m represents angular position of the motor shaft. The drive from the output of the gearbox is converted to a linear motion and moves the transmission cable (position L_c). The cable motion sets the joint angular position θ_j to the desired value.

The moment of inertia and viscous-friction coefficient referred to the output shaft of each motor were found by experiment, and the adjustable parameters of the system were set to obtain a slightly over-damped system. Full joint range actuation times were of about 1s for the finger and wrist roll joints and of about 0.5s for the wrist pitch joint. The maximum torques that were achievable at the joints of the robot hand were well in excess of the required values.

Preliminary tests with the prototype hand have shown that it is capable of grasping a wide range of objects of different shapes and sizes. Fig. 14 shows the hand using precision-type grasps to hold (a) a cylindrical object of 80 mm diameter and (b) a golf ball. In Fig 15, the hand is shown using power-type grasps to hold (a) a plastic bottle and (b) a tennis ball. Figure 16 shows the hand next to the master glove input device [12]. The hand is currently mounted onto a metal stand that can be manipulated by a human as shown in Fig. 17.

VI. Conclusion and Future Work

A five degree-of-freedom, teleoperated, servo-controlled, anthropomorphic robot hand and wrist system has been designed, constructed and demonstrated. The hand is capable of applying both precision-type and power-type grasps and can hold a wide variety of objects of different shapes and sizes. The study performed of human precision-type grasping has indicated that the index finger may contribute less than the middle and ring fingers in achieving a stable grasp under certain conditions. The robot hand, in conjunction with the glove input device, is currently being used in further studies of factors that affect dexterity in human and robotic grasping.

Limitations of the current hand prototype include the absence of force and touch feedback capability, as well as a very limited manipulation capability due to the small number of available degrees-of-freedom. Future work will focus on developing a more advanced version of the hand incorporating a greater number of degrees-of-freedom and haptic feedback, and capable of carrying out manipulation of an object. Other work will be directed towards mounting the existing hand and wrist system onto a mobile wheeled device incorporating a platform capable of translation and rotation about the vertical axis, in order to achieve an integrated mobile remote manipulator system that is capable of a wider range of teleoperation applications.

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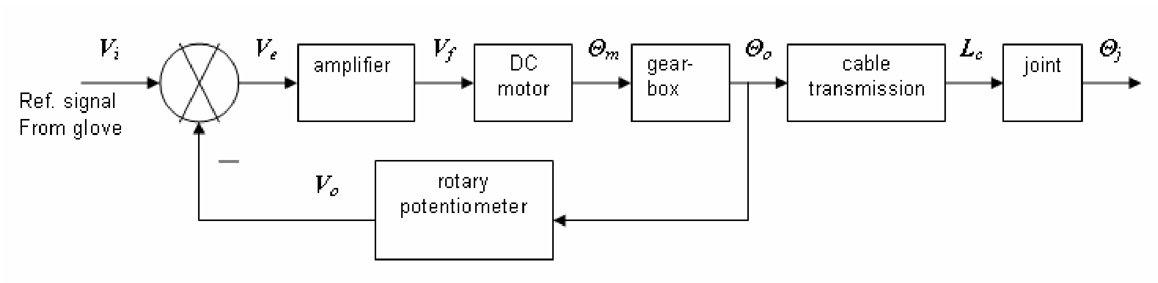
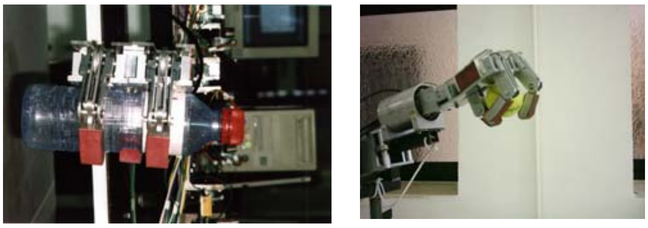


Fig. 13. Block diagram for the control system of the robot hand.

(a) (b)

Fig. 14. The robot hand using precision-type grasps to hold (a) a cylindrical object, (b) a golf ball.



(a) (b)

Fig. 15. The robot hand using power-type grasps to hold (a) a plastic bottle, (b) a tennis ball.

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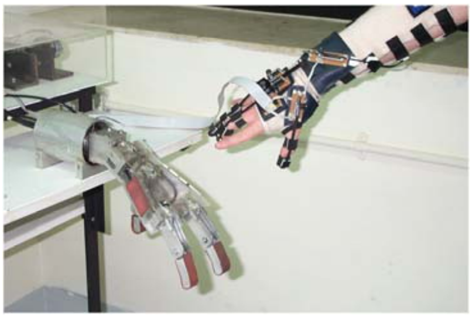

Fig. 16. The anthropomorphic robot hand and wrist, and the master glove input device.

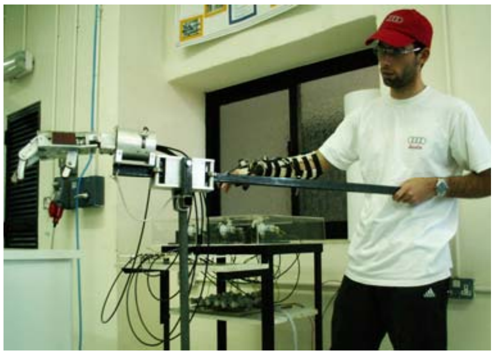

Fig. 17. The anthropomorphic robot hand and wrist, mounted on the metal stand and teleoperated using the glove input device.

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