Development of a Five-Finger Dexterous Hand without Feedback control: the TUAT/Karlsruhe Humanoid Hand*

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Abstract— **In order to realize performance gain of a robot or an artificial arm, the end-effector which exhibits the same function as human beings and can respond to various objects and environment needs to be realized. Then, we developed the new hand which paid its attention to the structure of human being's hand which realize operation in human-like manipulation (called TUAT/Karlsruhe Humanoid Hand). Since this humanoid hand has the structure of adjusting grasp shape and grasp force automatically, it does not need a touch sensor and feedback control. It is designed for the humanoid robot which has to work autonomously or interactively in cooperation with humans and for an artificial arm for handicapped persons. The ideal end-effectors for such an artificial arm or a humanoid would be able to use the tools and objects that a person uses when working in the same environment. If this humanoid hand can operate the same tools, a machine and furniture, it may be possible to work under the same environment as human beings. As a result of adopting a new function of a palm and the thumb, the robot hand could do the operation which was impossible until now. The humanoid hand realized operations which hold a kitchen knife, grasping a fan, a stick, uses the scissors and uses chopsticks.**

I. INTRODUCTION

In future society, it is expected that human beings and a robot live in offices, hospitals and homes together. In order to use a robot in such environments, a robot needs the ability to work in human being's environment. The function of an end-effector which actually works becomes important especially. For example, it becomes difficult for a robot to go in and out of the room freely if a doorknob cannot be turned. When working cooperation with a robot, it is necessary to prepare the tool that is for the robot exclusive use. The robot has to hold a soft thing or has to be able to do delicate work.

From such a reason, many researchers have developed the hand which has five fingers similar to human's hand [1-14]. If the actuator which is the same as the number of joints, and many sensors are given, the robot hand may be able to realize operation near human being. Therefore, many robot hands have many actuators, many sensors and a complex control system. However, this structure induces some problems. First, it is difficult to place a complicated mechanism into the size of a robot hand. Second, if a robot hand is heavy, it will have big influence on the actuator of arm or human being's arm. In fact, the weight of the hand increases the power consumption of the robot, gives a load on every joint and causes unstable behavior of the arm. Third, when many actuators and sensors exist, the control system becomes complicated. This is a main point for the artificial arm because a handicapped person might not be able to control a complex hand mechanism with many actuators. This is a problem important for a robot likewise.

For this reason, we propose to develop a lightweight five-finger hand driven by one actuator for a humanoid robot [15] and an artificial arm for handicapped person [16]. We call it the TUAT/Karlsruhe humanoid hand [17-19]. This hand realizes grip operation like a person easily according to the link mechanism which operates in cooperation. Fingers and palm will make the form automatically suitable for grasp, will generate suitable grasp force, and will grasp an object. Since the power of an actuator is optimized automatically and reached to a finger and palm, sensor and feedback system does not need. In performing delicate grasp like an operation of holding a straw, it operates to the position which is easy to grasp a finger beforehand using a few small servo motors for positioning. These small servo motors do not become the obstacle of the conventional linkage system. Thus, this hand without sensors and a control system can grasp an object easily as usual.

However, human's hand can perform many operations. In order to use it in the same environment as people, it is necessary to consider the operation which can be performed. For this analysis, we used the Kamakura's taxonomy [20]. This robot hand was not able to perform five kinds of operations about Kamakura's taxonomy as a result of the experiment. As a result of analysis, it turned out that a palm and MP joint's degree of freedom of the thumb are important for performing these operations. Therefore, this research aims at development of the robot hand which realizes operation to people by improving the function of a palm and a thumb (Figure 1). Five kind of the Kamakura's taxonomy which was not able to be performed was able to be realized as a result of improvement.

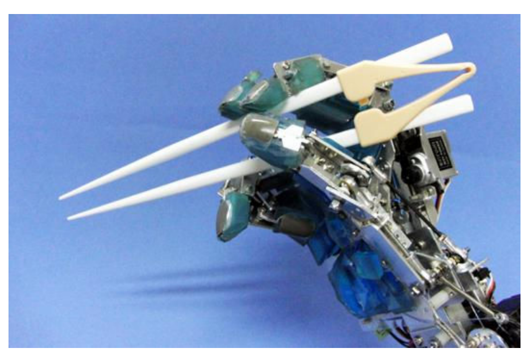

Figure 1. TUAT/Karlsruhe humanoid hand

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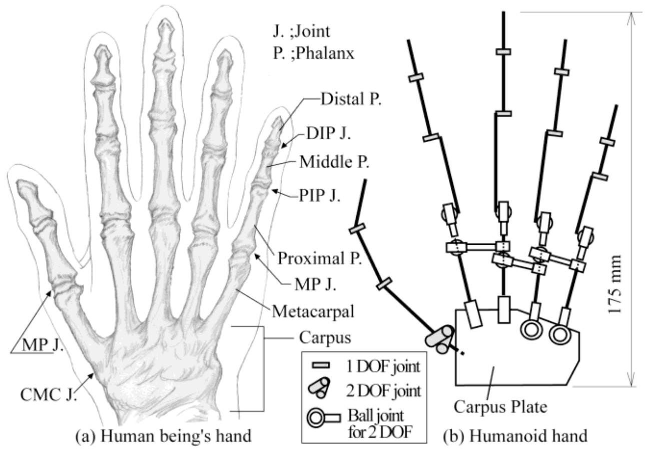


Figure 2. Structure of human beings and humanoid hand

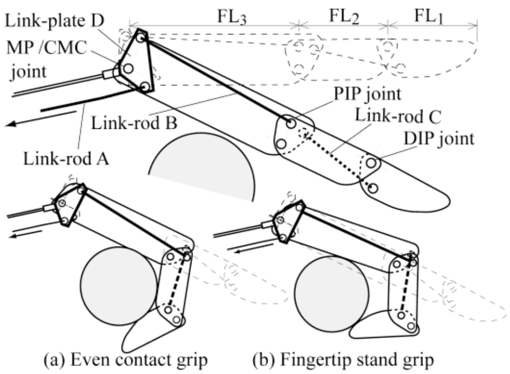


Figure 3. Mechanical works on each finger

II. Humanoid Hand

We built an experimental model of the humanoid hand suitable for the research purpose. The hand's size was determined based on a 27-year-old, 1.65[m] height and 55[kg] in weight healthy Japanese male. The humanoid hand has similar geometry; size from the bottom of a palm to a fingertip is about 175[mm], full width is 110 [mm]. This hand realizes natural grasp form like human being's hand by the work of various mechanical structures.

A. *Structure of a hand and fingers*

The skeleton structure of human being's hand is shown in Figure 2(a). The first four fingers consist of three joints, and each has four degree of freedom. The joint which exists in a palm has two degree of freedom, and is called the *metacarpophalangeal* (MP) joint. These MP joints have the working range of about 120[°] at the flexion-extension direction and about 30[°] at the adduction-abduction direction. Four fingers have two the *interphalangeal* (IP) joints other than MP joint, it has one degree of freedom, and a range of motion is approximately 90 degrees [21]. Then we constructed a palm using a ball-joint rod with two degree of freedom (2DOF). The metacarpal rods of the index and the middle finger were fixed to the carpus board. The metacarpal of the ring and the little finger were fixed to a carpus board using 2 DOF ball-joint, and it enabled it to move by connecting each like a tendon using short ball-joint like human being (Figure 2(b)). Thus, the palm of the humanoid hand was able to have a flexible motion like human being.

TABLE I. Giometry of each finger

Part	Index	Middle	Ring	Little	Thumb
FL1[mm]	28.5	29.5	29.5	28	30.5
FL2[mm]	20	27	25	15	26
FL3[mm]	40	43	40	32	58

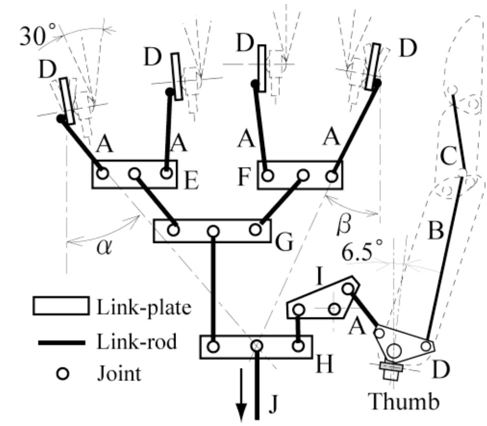


Figure 4. Harmonic linkage mechanism for fingers motion

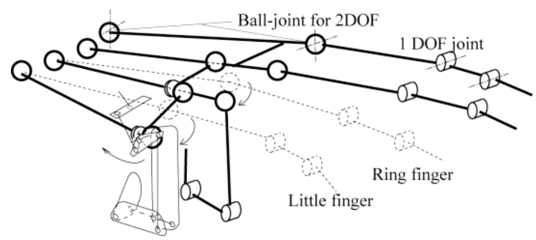


Figure 5. Movement motion of the palm part

B. *Mechanical design of finger*

Four fingers and thumb require a complicated mechanism. Figure 3 shows the finger's linkage mechanism. The length between the joints of each finger is shown in Table I. To grasp an object, the link-rod A pulls the link-plate D and the finger moves and keeps its form. If the proximal phalanx part touches an object, the following happens: the link-plate D moves independently while the middle proximal phalanx part is moved by the link B. The link C attached to the proximal phalanx part pulls the distal phalanx part. Finally, the finger curls around the object with a small grasping force (Figure 3(a)). Like a heavy object grip, when power strong against a fingertip is required, a finger rotates to fingertip stand form automatically (Figure 3 (b)). This mechanics has several good characteristics similar to the human beings movements and it can automatically change the grip shape in response to the object condition. Therefore it can be very useful to control systems.

C. *Harmonic linkage mechanism and palm design*

Figure 4 shows the linkage system of the finger motion. Four fingers and thumb are linked by the link-plate E, F, G and H. Since it is not being fixed to the carpus board, these plates can be moved freely. The link-plate I is being fixed so that it may rotate by the middle axis. By using weak springs, each finger can easily return to its index position. Each link starts working by itself with the strain of the link-rod A when the link-rod J is pulled. Each finger will be moved because link-rods A pulls each finger through the link-plate D. The link-plate E starts a rotation centered on a joint point of the link-rod A of the little finger when the little finger touches the object to be grasped. The link-plate G also starts a rotation centered on a joint point from the link-plate E when the ring finger touches the object, while the index finger, middle finger and thumb keep moving. Thus, every link keeps being moved by the link-rod J until every finger touches the object. Therefore, each link moves to keep the balance of the strain force on every link when the contact force of several fingers becomes suddenly weak. Finally, the contact force of every fingers becomes evenly again. Additionally, the link-plate E affects the metacarpal rods of the little and ring fingers towards the object if the ring and little fingers touch the object (Figure 5). More stable and safety grasping of the object were able to be achieved because the fingers and the palm are capable of evenly touching the object.

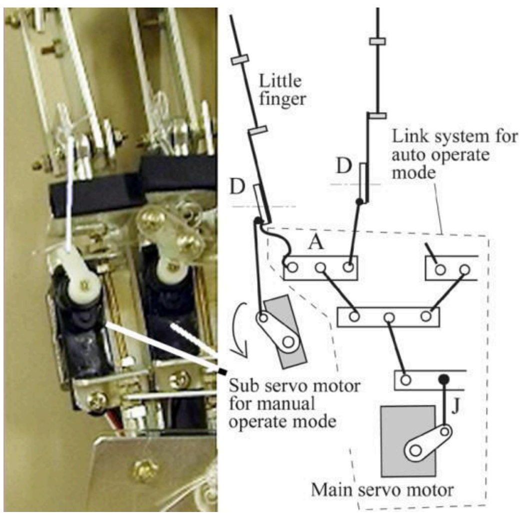
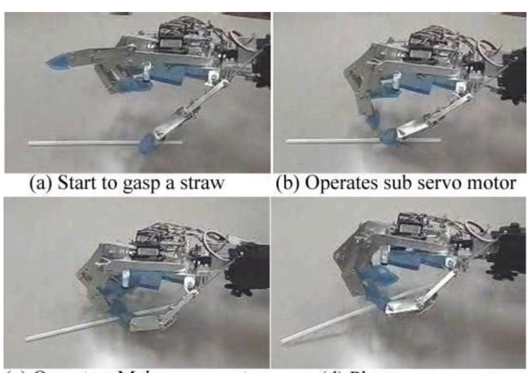


Figure 6. Manual operate mode with sub servo motor


(a) Start to gasp a straw (b) Operates sub servo motor

(c) Operate a Main servo motor (d) Pic up a straw

Figure 7. Situation of manual operate mode (tip a straw)

TABLE II. MAIN SPECIFICATION OF EQUIPMENT

Kinds	Main specification of equipment	
	Item/Name	***Specification***
Main servo motor	RS-405CB (Futaba co.)	Max torque: 4.7[Nm] at 12[V]
Sub servo motor	W-150 Power (Waypoint)	Max torque: 0.38Nm at 4.8[V]
Control bord	RCB-3HV (Kondo Kagaku co.)	This board can connect 24 servos
Battery	Ni-Cd battery (Kondo kagaku co.)	DC 6[V]
Wireress controller	VS-C1 (Vston co.) & Rev-1(Craft house co.)	Frequency: 2.4GHz Reach distance: 15m

The link-plate E of the little finger is located at an angle α to the link-rod J. The link-plate F of the index finger is also located at an angle β (Figure 4). Therefore, both fingers can grasp the object with an adduct force and the object can be touched with the side surface as it would be handled by a human being. Since this link mechanism adjusts grip uniformly automatically, the feedback control of a motor (call a Main servo motor) which pulls a link-rod J is unnecessary. The hand can hold an object by only adjustment of the rotation angle of a motor for according to the size and softness of an object. We call this system is a harmonic linkage mechanism.

III. MANUAL OPERATE MODE

It is not easy to evaluate the performance of a hand. For this reason, it evaluated using the Cutkosky's taxonomy [23]. As a result of experimenting, the hand was not able to realize five kinds of operations (Large diameter, abducted thumb, light tool, thumb-3 finger and thumb-2 finger) in 16 kinds in the Cutkosky's taxonomy. There is a factor of this result in the ability of each finger not to operate independently.

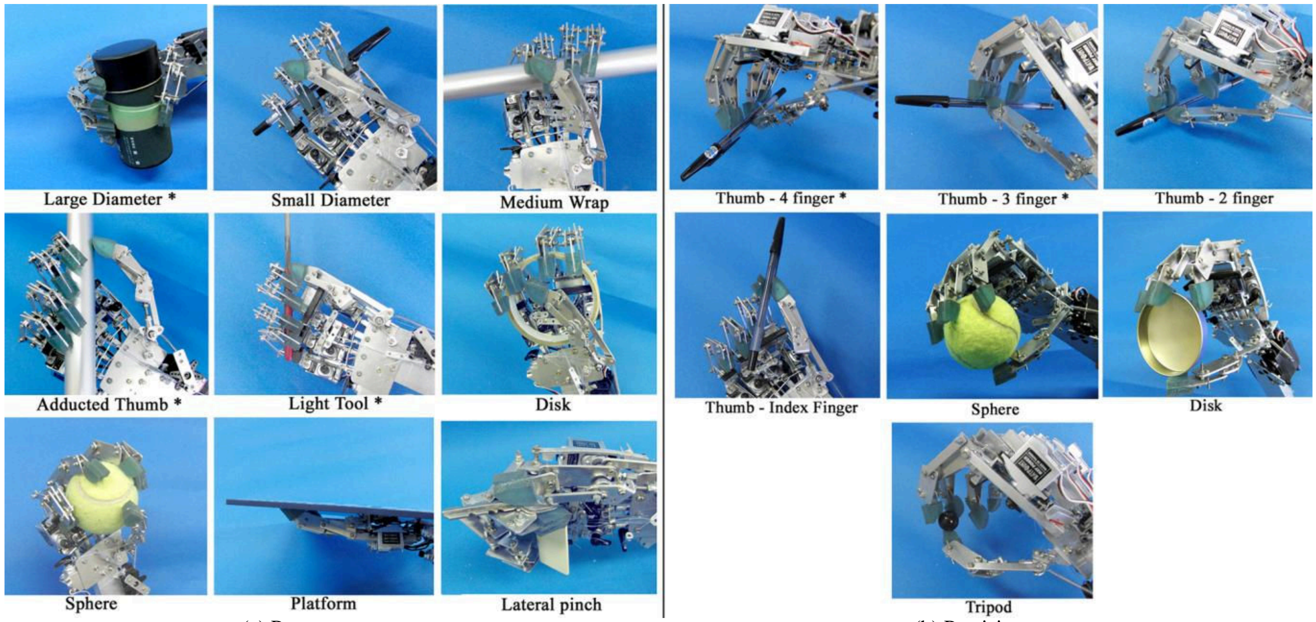
A. *Each finger operate system*

In order to realize the function to operate each finger individually, without losing the conventional grasping function, small servo motors (call a sub servo motor) have been arranged between metatarsals. These sub servo motors can operate link-plate D of each finger individually by a wire. Individual operation of each of this finger is called a manual operate mode. Thus, in addition to the wire for conventional linkage system with the main servo motor (call an auto operate mode), the wire for manual operate mode by the sub servo motor is also connected to the link-plate D (show in Figure 6).

Operation of the thumb is very important for fine work. For this reason, it enabled it to operate a CMC joint of the thumb finger in the two directions. For this reason, two sub servo motors were given to the thumb. The sub servo motor can operate a CMC joint of thumb in the adduction direction and the flexion direction. One of the sub servo motors is placed by the palm, it operates the link-plate D of the thumb in the flexion direction, and another is placed on the dorsum of hand side and operates the link-plate D in the adduction direction. Thus, the number of sub servo motors is six.

B. *How to grasp by a manual operate mode*

By using the manual operating mode system, it became possible to operate each finger to a satisfactory position. When holding the thing which needs delicate operations, such as a straw, each finger makes a pre-shape form for holding a small object by the sub servo motor. After bringing a fingertip close to an object, it grasps using the main servo motor with linkage system. Since the function of the linkage system functions as before, grasp can be performed stably. Thus, it became possible to operate a fingertip intricately according to the candidate for work. As a result, the adaptability to various objects and work improved. The situation where the hand is operated by manual operate mode is shown in Figure 7. Sub servo motors for middle, ring and little finger are operated to make a pre-shape of tip grip motion. Next, the sub servo motor for index finger is roughly operated so that an index finger



(a) Power grasp (b) Precision grasp

Figure 8. Result of grasping experiment of new model based on Cutkosky's taxonomy [22]

may approach a straw. Similarly, the thumb also operates two sub servo motors for thumb and brings them close to a straw. Since the power of a fingertip will be self-adjusted after this if the main servo motor is usually operated to a passage, the hand can pick up a straw easily without feedback control.

C. Result of grasping experiment of based on Cutkosky's taxonomy

We constructed a humanoid hand which has the main servo motor and six sub servo motors. The main materials of this hand are A5052P and A2024, and weight was 490 g. The main specifications of equipment are shown in Table II. The result of having actually operated the hand based on the Cutkosky's taxonomy was shown in Figure 8 [22]. The operation with a mark (*) in Figure 8 became possible by new structure and using a manual mode.

By moving a thumb and each finger to a suitable position by a manual mode beforehand if it is necessary, all the operations of Cutkosky's taxonomy were able to be performed. However, in a part of precision operations (Thunb-4 finger, sphere and disk), several fingers needed to touch on the floor. This is because a palm must be bending to perform the target operation. Bend function of a palm is realizable if a sub servo motor is added, although structure and control system will become complicated. Therefore, you should judge whether it adds according to the purpose if you want to do perfectly.

IV. KAMAKURA'S TAXONOMY

The operation which a hand should perform exists innumerably in daily life. In order to investigate how much a hand can grasp these, we decided to use the grip classification of Kamakura [20]. From a viewpoint of the occupational therapist that performs rehabilitation, Kamakura has advocated the grip classification (Figure 9) based on a grip in daily life. The meaning of an abbreviation : *Power grip – Standard type* (PoS), *Power grip – Hook type* (PoH), *Power grip – Index finger extension type* (PoI), *Power grip* – *Distal type* (PoD), *Power grip – Extension type* (PoE), *Lateral grip* (Lat), *Tripod grip – type I* (T-I), *Tripod grip – type II* (T-II), *Tripod grip – type III* (T-III), *Parallel mild-flexion grip* (PmF), *Tip grip* (Tip), *Surrounding mild-flexion grip* (SmF),

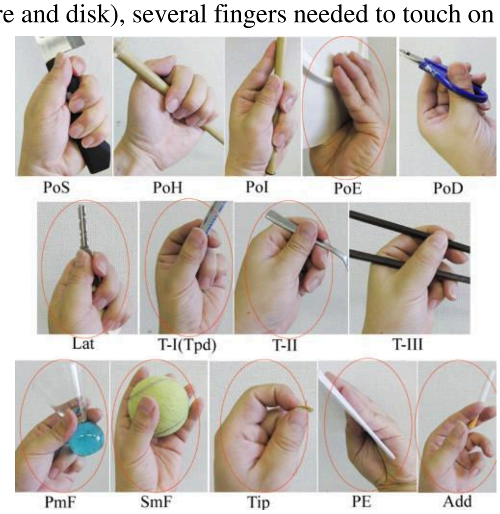


Figure 9 Kamakura's taxonomy [20]

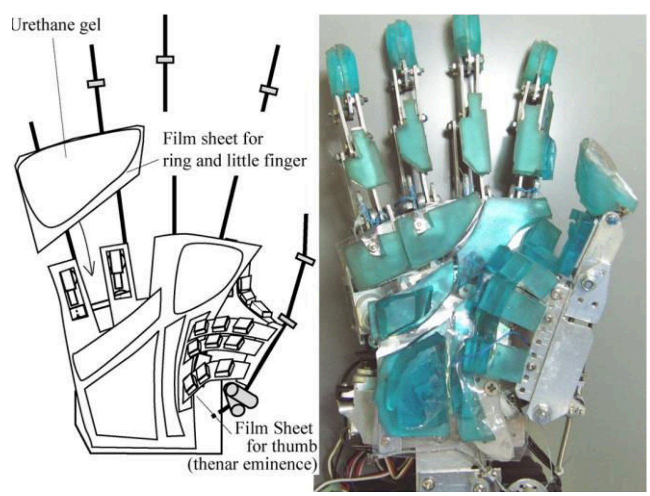


Figure 10 Structure of flexible palm sheet like human being

Parallel extension grip (PE) and *Adduction grip* (Add)). In this grasp classification, the operation which humanoid hand was able to perform was only the operation shown with red circles. The insufficient of function of a palm and the thumb is mentioned as this factor.

A. *Structure of palm sheet*

It is important that a palm contacts an object if we want to stabilize grasp. For example, in a cylinder grip (PoS) and stick grip (PoI) of Figure 8, it can grasp by the palm, the hypothenar eminence and thenar eminence touch in addition to fingers. Similarly, the thenar eminence is important also at a grip of a stick (PoH). Plica interdigitalis between an index finger and a thumb always forms an arch between an index finger and a thumb. This arch plays an important role in a knob grip of a pipe, a doorknob, chopsticks, etc. For this reason, we developed a flexible palm sheet structure like human being as shown in Figure 10 and Figure 11. The palm consists of a flexible film sheet and urethane gel. Urethane gel has divided and arranged so that a motion of a palm may not be barred. Film sheet was also divided into two parts. The film sheet had a double layer structure so that it may not interfere with a motion of a palm or a finger. Therefore, the position of urethane gel was the same as that of human being's palm lines.

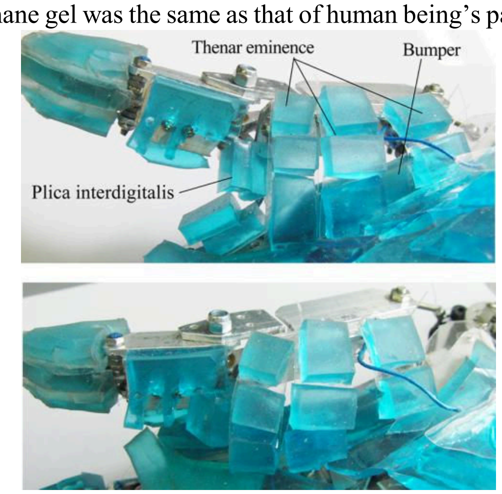


Figure 11. Structure of Plica interdigitalis and thenar eminence

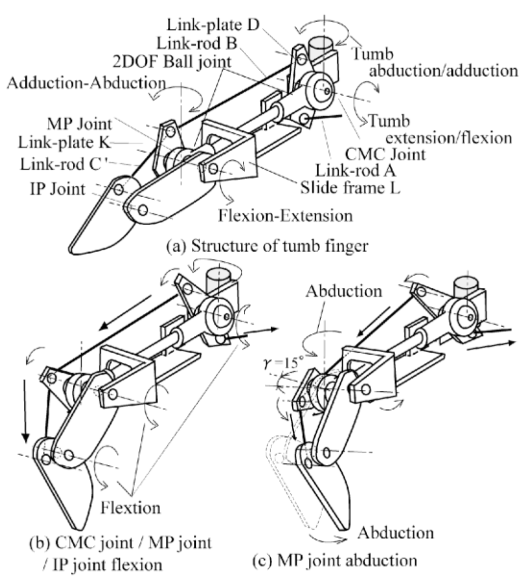


Figure 12. Mechanical works on new design thumb

The structure of a thenar eminence and plica interdigitalis are shown in Figure 11. In order to realize the pliability and stability of a thenar eminence, in addition to the same film sheet structure as the palm sheet, the bumper frame was prepared in the inside of film sheet of the thenar eminence . This film sheet is being fixed to the frame of a thumb's metacarpals and a palm. For this reason, if the thumb makes flexion or adduction, the film sheet will bend so that it may swell. A bumper frame supports this film sheet from the back side when a thenar eminence contacts an object. Thus, the film sheet can generate the stable contact force.

B. *Improved the degree of freedom of the MP joint of thumb*

In parallel grip operation, such as PmF, an index finger and a thumb need to become parallel like tongs. This parallel operation is operation obtained when the thumb's MP joint makes abduction. This function is very important in order to perform specific grip operation (PoD, T-III, etc.) stably in addition to typical parallel grip operation (PE and PoF). For this reason, we newly developed the structure of the thumb (Figure 12). The joint of the thumb was changed into 2DOF ball joint. Moreover, the pairing element of link plate C and IP joint on distal phalanx were exchanged. If the link plate D is pulled by the link A, a thumb is crooked toward an object as usual. If the thumb reaches the limit of working range or a middle phalanx contacts an object, a distal phalanx start rotation in the direction of flexion. A MP joint begins rotation automatically in the direction of abduction if a distal phalanx reaches the limit of a movable range or an object is contacted. In addition, when the distal phalanx touches the object in adduction and the direction of an outward swing, IP joint and MP joint rotate only in the flexion direction automatically (CMC joint can rotate flexion direction and adduction direction).

V. RESULTS AND COMPARISON

We constructed a new humanoid hand with the flexible palm and the new structure thumb. This hand has 24 DOF, and after it makes grip form by small actuators if needed, it can grasp various things only by operating one actuator. Operation of the hand is carried out by choosing the sequence pattern saved on the control board. A sequence pattern can be easily chosen using a wireless controller (similar to PlayStation's game controller). For example, if button with a controller for manual mode is pushed, each finger of hand will change to the form for Tip grip by sub servo motors (like Figure 7 (b)). If button for auto operate mode is pushed, the main servo motor will begin to rotate and this hand can grasp an object easily. The controller is assigning several buttons for auto and manual operate mode. Kinds of button for auto operate mode and rotation angle of main servo motor are shown in Table III. After uniting the position of the hand, grasp is performed only by choosing appropriately the button for auto operate mode suitable for the size of the object. When using the hand for the humanoid robot, it is sufficient that the control system of robot generates operating signals instead of pushing the button. A current of servo motor will increase if this hand holds an object. Therefore, if this current is detected, the robot is able to check whether the hand has held the object.

TABLE III. BUTTONS AND ROTATE ANGLE OF MAIN SERVO MOTOR

Button of controller	×	R1+O	R1+Δ	R1+□	R1+×	O	Δ	□
Rotate angle [°]	0	55	90	135	168.75	191.25	211.5	234

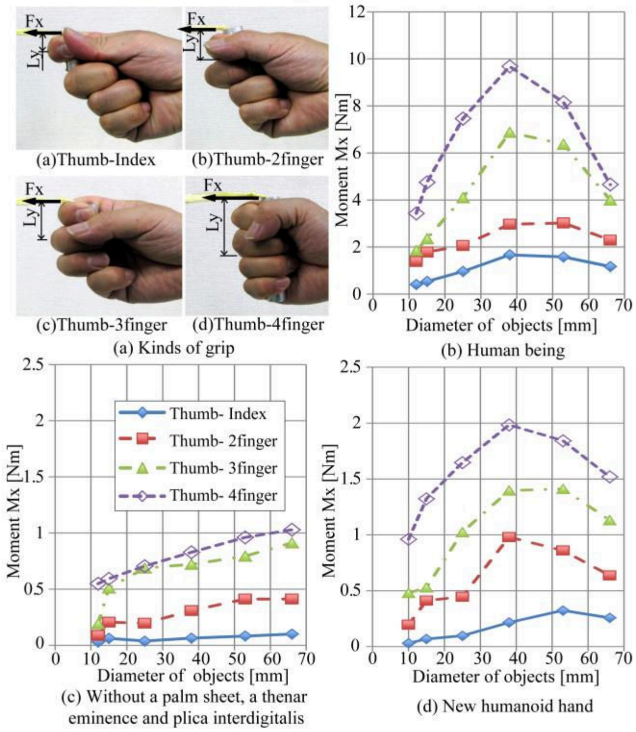


Figure 13. Results of grip force about human and robot hand

A. *Effect of palm sheet and thumb structure*

In order to verify the effect of the parts adopted newly, we conducted the experiment about grip force. The problem of the PoS operation was being unable to grasp a cylinder thing stably. Then, for the purpose of verifying the effect of a flexible palm sheet, a thenar eminence and plica interdigitalis, as we were shown in Figure 13, when load was added horizontally, we investigated the full limits which continue having five kinds of cylindrical objects (diameter of objects are 15, 25, 38, 56 and 66[mm]) grasped. In order to verify the effect of new structure, the experiment was conducted on four kinds of operations shown in Figure 13 (a). Moreover, the result on which the human being who became a model of the hand for comparison conducted the same experiment, and the result performed where a palm is eliminated from a hand are shown in Figure 13 (b) and (c). The hand which experimented in Figrure 13 (c) does not have the flexible palm sheet, a thenar eminence and plica interdigitalis, like a conventional robot hand, as shown in Figure 8. A result of new humanoid hand is shown in Figrue 13 (d). The vertical axis of a graph shows the moment Mx. Mx is obtained by the distance Ly from the halfway point of the grasped finger to the edge of a palm and the load Fx added to this point by a spring balance.

$$M\chi = F\chi \times Ly. \quad (1)$$

This is because the rotation moment by the load to one way by a contact force, a pressure, a shock or weight is added strongly, when it has a kitchen knife or a long stick at the end like the PoS operation. The horizontal axis of the graph shows the diameter of five kinds of cylindrical objects. Although the difference of an output was large when Figure 13 (b) was compared with Figure 13 (d), it turned out that the whole tendency was very well alike. On the other hand, although the tendency of an output of Figure 13 (c) and Figure 13 (d) was near, tendencies differ clearly. In Figure 13 (c), withstand load was large in proportion to the cylindrical object's diameter. The hand which experimented in Figure 13 (c) does not have a flexible palm sheet, a thenar eminence and plica interdigitalis. For this reason, when grasping a cylinder thing, this hand will be held, using a thumb and a palm like tongs. Although this grasp is suitable for grasping a large object, it is not suitable for a small object. As explained above, this humanoid hand can grasp various size objects stably like people by having a flexible palm sheet, a thenar eminence and plica interdigitalis.

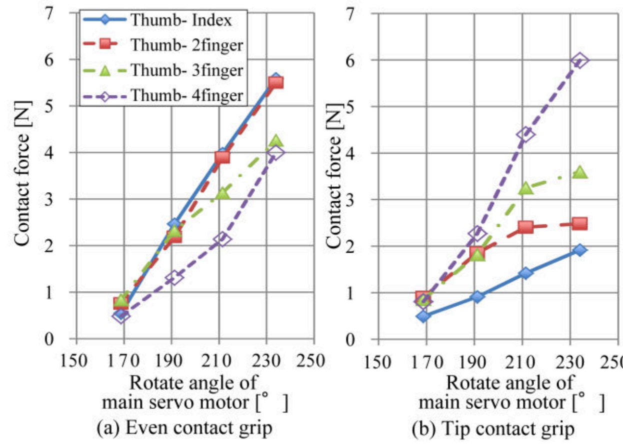


Figure 14. Results of contact force at grip type

B. *The action which excepts feedback control*

In order to grasp an object stably, it is required to control contact force appropriately. This hand has the function to adjust contact force automatically. In order to investigate this work, we conducted the experiment about contact force. The contact force at the time of object grasp was measured using the pressure sensor attached to the point of the index finger of a hand. The pressure sensor used the PSCR sensor (pressure-sensitive conductive rubber, PCR Technical co.) 0.5 [mm] in thickness, and 8 [mm] in diameter. The experiment was conducted on two kinds (even contact grip and fingertip contact grip), the case where the palm of a hand contacts an object like Figure 13(a) and holding an object only by fingertip like Fig. 8 (Thumb-Index, Thumb-2 finger, Thumb-3 finger and Thumb- 4 finger). The former object used a cylinder thing 38 [mm] in diameter, and the latter used a 10 [mm] thick square pipe. In order to check the same situation, the main servo motor was always operated using four kinds of same buttons (R1+×, O, Δ and □). Rotation angles are 168.75, 191.25, 211.5 and 234 [°], respectively.

An experimental result is shown in Figure 14. Contact force was increasing in proportion to the rotation angle of a motor. However, the tendency became reverse clearly. In even contact grip, the increasing rate of the contact force in the grasp method of the Thumb-4 finger was lowest. This is considered to be based on the function of the hand to which it is going to expand the area in contact with an object. Contact

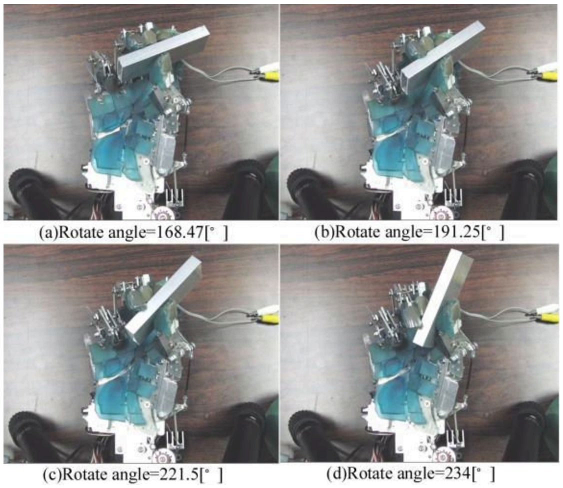


Figure 15. The automatic change function of a grasp posture

force arises with pressure. For this reason, contact force will become low if a contact area becomes large. Even if it operates a motor roughly that hand can grasp an object because the rate of change of contact force is low and contact force of only a part does not increase. When man also grasps an object, it only grasps roughly so that an object may not be dropped or it may not break.

On the other hand, in fingertip contact grip, the grasp method of the Thumb-4 finger was the highest and the grasp method of the Thumb-Index was the lowest. This cause is because load cannot escape into other portions in the Thumb-4 finger type fingertip contact. By this grip method, in order to add almost all loads to a fingertip, it is thought that the rate of change was high. In the case of the grip method of the Thumb-3 finger to the Thumb- Index, excessive load is consumed when the finger and palm which do not contact will bend. Furthermore, a hand operates a finger and a palm automatically so that an object can be grasped more strongly (Figure 15). Therefore, it is thought that the increasing rate of the contact force in these operations does not become high. Contact force was hardly going up in operation of the Thumb-Index type fingertip contact (Tip grip). Usually, in operation of tip grip, in order to grasp an object, it is necessary to adjust contact force very delicately. By this characteristic, the hand can grasp an object by tip grip, even if operator operates the main servo motor roughly. For example, even if the object which breaks easily like potato chips is held and it adds contact force by the main servo motor rotation, it does not break.

Therefore, since this hand has the function to adjust contact force automatically structurally, a feedback control system is not needed in order to grasp an object stably.

C. *Result of Kamakura's taxonomy*

Experimental result of having performed the Kamakura's taxonomy using the improved hand with manual operate mode system is shown in Figure 16. The grip experiment was conducted using the common object as same as used in Kamakura's taxonomy. These are a kitchen knife, a Japanese style fan, a, stick, a dish, a scissors, a key, a spoon, a chopstick, a small grass, a tennis ball, a drawing pin and a sheet. By moving a thumb and each finger to a suitable position by a manual mode beforehand if it is necessary, it is evident that every grasp type is sufficiently well holding. Five kinds of grip operations which were not completed have also been performed stable.

All operations other than a grip of chopsticks (T-III) were able to be carried out stably. In grip operation of grip a kitten knife (PoS) and stick (PoI), it is changing so that a palm sheet and a thumb ball may coil around the handle of a kitchen knife or a stick firmly. When the kitchen knife was actually used, the hand was able to cut hard foods such as a radish and a potato. Operation of grip a fan (PoH) can be easily realized because MP joint of the thumb had degree of freedom of adduction direction and abduction direction. About operation of using a scissors (PoD) or using a chopstick (T-III), the thumb and an index finger can be moved now so that it may adapt itself to the working range of scissors or chopstick because MP joint of the thumb carries out adduction. In operation of grip a chopstick (T-III), it has played the role also with a plica interdigitalis important for the stability of chopsticks. However, the operation which opens chopsticks (T-III) was not able to be reproduced about a grip of chopsticks. For this reason, grip operation with chopsticks was able to be realized by attaching an auxiliary implement to chopsticks. By having attached the auxiliary implement, the humanoid hand was able to hold even a grain of rice in addition to ordinary foods using chopsticks.

The humanoid hand was also able to perform about other daily life operations. Examples are: turned a doorknob, using tools (saw, pliers, screwdriver, etc.), eat food (bread, snacks, etc.), grasp a 1.5-liter PET plastic bottle and open an egg.

VI. CONCLUSIONS

In this paper we presented that the improvement proposal and grip experimental result about the humanoid hand which we have developed. This humanoid hand is moving a finger and a palm and adjusts grasping force automatically with one actuator, and was able to grasp many objects. Furthermore, in order to grasp many objects, we developed the independent operation structure of the finger by six small servo motors. These small servo motors are used in order to make pre-shape form for grip, and final grip force is made by one servo motor as usual. Therefore, the humanoid hand does not need a touch sensor and feedback control system.

In order to perform the quality assessment of the hand, we experimented about activities of daily life. Five kinds of operations were not fully able to perform when the Kamakura's taxonomy was used as an indicator of an experiment. As a result of analyzing a cause, it turned out that the function of MP joint of thumb and palm are insufficient. Therefore, we developed a two degree of freedom structure of MP joint for the thumb and the flexible palm sheet like human being. According to this configuration, although operation of chopsticks had a slight restriction, all kinds of Kamakura's taxonomy were able to be performed by simple control system without feedback control. As a further result, we confirmed that with the humanoid hand, it is possible to fulfill our demands for typical manipulation tasks of humanoid robots and artificial arms.

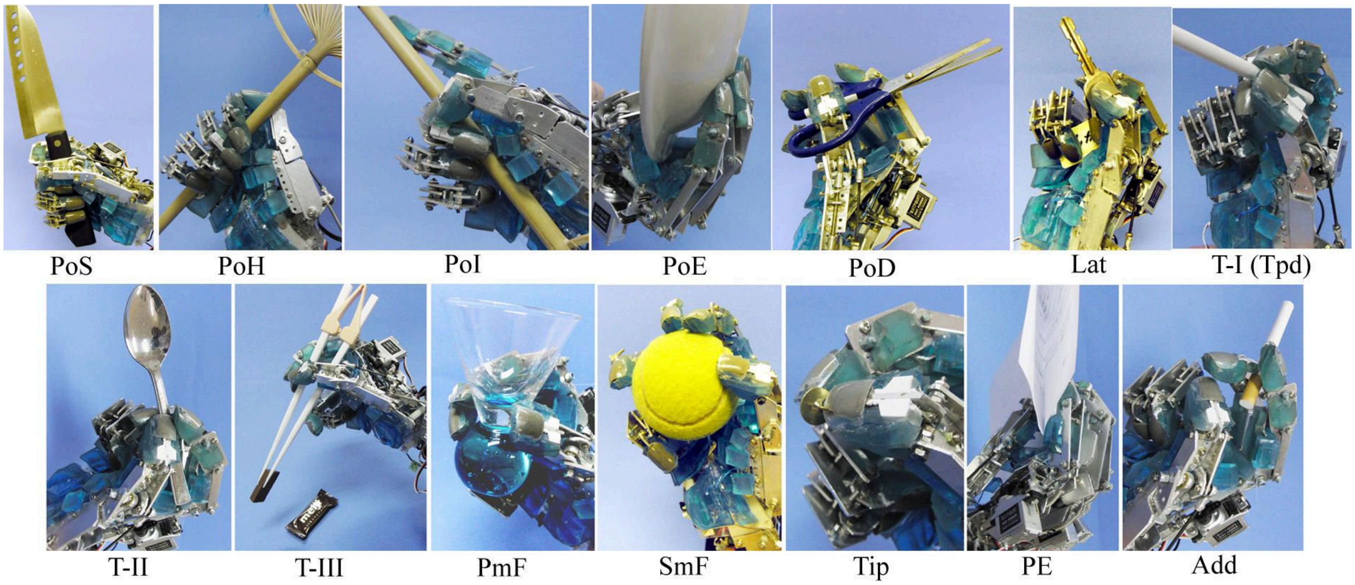


Figure 16. Result of Kamakura's taxonomy [20]

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