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Dexterous Hand-Arm Coordinated Manipulation using Active Body-Environment Contact

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***Abstract*—Human-symbiotic humanoid robots that can perform tasks dexterously using their hands are needed in our homes, welfare facilities, and other places. To improve their task performance, we propose a motion control scheme aimed at appropriately coordinated hand and arm motions. By observing human manual tasks, we identified active body-environment contact as a kind of human manual skill and devised a motion control scheme based on it. We also analyzed the effectiveness of active body-environment contact in glass-placing and drawer-opening tasks. We validated our motion control scheme through actual tests on a prototype human-symbiotic humanoid robot.**

Key words: *Active Body-Environment Contact, Stable Object Manipulation, Coordinated Motion of Hand and Arm, Motion Control Scheme,*

I. Introduction

SEVERAL kinds of machines that use robot technology have recently been developed by many companies, and robots are entering our daily lives. The most basic tasks in daily life are very simple ones such as picking up an object, transferring it to another place, and placing it there. These tasks are often accompanied by other tasks such as opening and closing a room door or a drawer. These tasks are performed very often in daily life, and they are very onerous for elderly or disabled people who have great trouble standing up and sitting down. Hence, research projects to develop a humanoid robot that has human mimetic hands and arms are now proceeding in several countries [1][2]. One of their research purposes is daily life support using humanoid hands and arms.

One of basic and important requirements for the robotic replacement of the abovementioned tasks is the behavior control. The behavior control includes object, environment, and human recognition through robot vision and behavior planning system. Most researchers in this field have focused on these issues, and many algorithms have been proposed [3][4]. Nevertheless, remarkably few researchers have focused on task performance such as the speed and smoothness of motion during task execution. We think that this is also important, since human-symbiotic robots are going to provide the daily life support. We need to discuss hand and arm dexterity for high-performance task execution in daily-life environments. For the discussion this issue, we have to make mention of the uncertainty in daily-life environments. Inevitably there is model error of the object properties such as size, stiffness, friction coefficient of surface, because there are differences among the actual individual objects and their properties vary across the ages. The accuracy of object position and posture recognized through the robot vision vary due to lighting condition. And it is very difficult to recognize with high accuracy on any lighting condition. We cannot estimate all these errors in our daily life environments. The uncertainty makes the task performance unstable. We need to discuss the dexterity to achieve high-performance task execution which is regardless of the uncertainty in our daily life environment.

In other research fields, on the other hand, a lot of researchers have focused on dexterity. For robust grasping and handling corresponding to the uncertainty, researchers developed many kinds of multi-finger hands with the passivity such as mechanical spring in the finger joint, soft material on the finger surface [5][6]. And also researchers developed many kinds of manipulators with unique passive mechanisms in its joint [7]. Confidently we can tell that the passivity is very useful for humanoid robot aiming to work in daily life environment. Moreover, corresponding to the uncertainty, a lot of control methods have been proposed; robust grasping or handling control methods on multi-finger hand, force or trajectory control methods on manipulator [8][9]. Humanoid robots have both hands and arms like a human, and these control methods can be applied to each part. But an important issue still remains: a proper coordination scheme for the hand and arm is needed for dexterous task execution. Few studies have focused on coordinated hand-and-arm motion [10].

Therefore, our research purpose is to develop an appropriate hand-and-arm coordination scheme, aiming to

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achieve high-performance task execution which is regardless of the uncertainty in our daily life environment. In this paper, firstly we introduce the active body-environment contact as a human hand working skill and propose a motion control scheme using that skill. We describe experiments using an actual humanoid robot which has the passivity in its body part, and validate our control scheme from the viewpoint of task performance. And from the experimental results, we discuss the relationship between the uncertainty in the daily life environment and the dexterity which consists of the passivity and the active body-environment contact.

II. Hand-Arm Coordinated Motion using Active Body-Environment Contact

A. Picking up a Human Hand Working Skill from Observation

First, we introduce a human manual skill that we identified by observing human motion in everyday activities. Service staff in a restaurant or cafe are professional performers of the basic tasks mentioned in Section I. They can carry dishes, lay a table, and clear the table both quickly and carefully. Their motion is very rapid, smooth, and courteous. Observing their movements when placing a glass on a table, we noticed that they put the sides of their little and ring fingers down on the table surface before the glass made contact with the table. Before the contact between body and table, the server's motion was very fast. In contrast, after this contact, it was much slower, and the glass was placed on the table very gently (Fig. 1). Non-professionals usually place a glass directly on a table without inserting body-table contact, so the glass sometimes makes a loud impact. This happens when we are in a hurry or when there are obstacles on table that occlude the spot where we intend to place the glass. In such situations, professional servers never make mistakes. The human manual skill that we identified from this observation is the use of active contact between the body and the environment.

Another example is that we usually put our elbow, forearm, or wrist down on the table when write with a pen. This lets us write without having to bear the full weight of the arm and hand while performing the task. This skill makes the task more comfortable. Without it, our arm would tremble slightly in free space and we would be unable to write neatly at the target location. We can tell that this skill improves our dexterity. The same active-environment contact appears when we solder with a soldering gun or to thread a needle. In addition, when people open a drawer, some of them make active contact between their thumb and the fixed vertical desk surface above the drawer. The door of a refrigerator is usually held shut by a magnet and we must apply enough force to the door to overcome this in order to open it. It also takes considerable force to open an old sliding window that no longer slides smoothly. These forces are not so small for women and children. Furthermore, once the resistance has been overcome and the drawer, door, or window has been released, it starts to move at high speed. And the woman or child who opens this drawer reels back from this sudden alteration. In the case of a refrigerator, this can result in the contents in the door being jerked about and they may fall to the floor. Active body-environment contact, such as using the thumb when opening a drawer, can control the movement in this situation, and this skill is more courteous way to open a drawer.

All the tasks in these examples have the common feature that of a discrete change in the restraint condition of an object. Task performance tends to be unstable at this change. Hence, we think that coordinated hand-arm motion using active body-environment contact is a kind of manual skill that prevents task performance from becoming unstable at the time of a discrete change in object restraint condition.

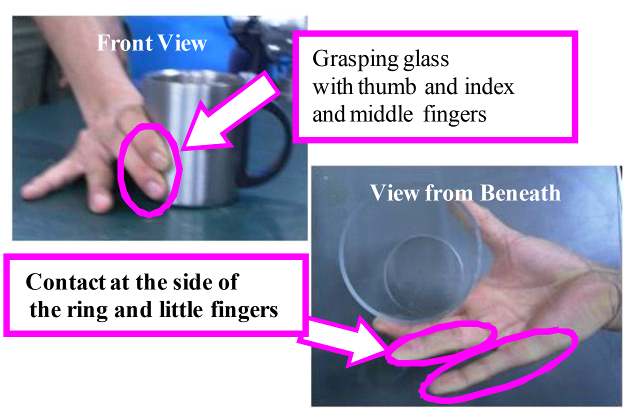


Fig.1. Motion of a Skilled Server Placing a Glass gently onto a Table

B. Motion Control Scheme based on Active Body-Environment Contact

In this section, we propose a motion control scheme to achieve coordinated hand-arm motion using active body-environment contact. For such contact, this scheme must be able to control both the condition at the contact between body and environment (hereinafter BE contact) and the condition at the contact between body and object (BO contact). To meet these functional requirements by simple means, we separate all the actuators implemented on the robot hand and arm into two groups. The BO contact condition is controlled by the motion of actuators in one group (task executing system) and the control BE contact is controlled by those in other group (bracing control system). To divide the actuators into these two groups, we introduce the concept of an object-body-environment (OBE) loop. The OBE loop is

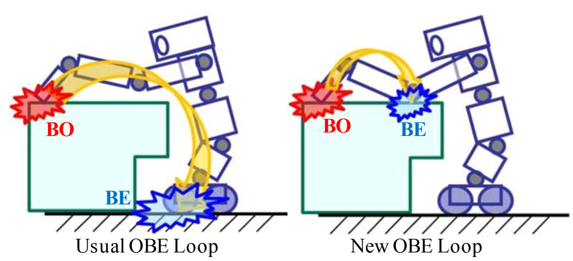


Fig.2. OBE Loop produced by Active BE Contact

defined as the path between BO and BE contacts connected by the body parts. A humanoid robot usually has a very large OBE loop between the bottom of the foot (or vehicle) and the hand via all of the body parts, so active BE contact clearly produces a new OBE loop that is much smaller (Fig. 2). Actuators involved in the new OBE loop are included in the task executing system, while all the other actuators are included in the bracing control system. The control method for each system will change according to the task and the definition of its performance. In the following sections, we apply this motion control scheme to specific examples of basic tasks and introduce the control methods we installed to improve task performance.

Some researchers have focused constraining the intermediate point of the redundant manipulator with the environment [11], which they called bracing control. The research purposes of almost all the previous studies were control methods for specific purposes such as joint torque minimization. These researches don't make mention of how appropriately their methods can control the state of BO contact. Our research purpose is to improve the dexterity in manual tasks by motion control. There is a big difference between this purpose and previous ones.

III. Application of Our Control Scheme for Glass Placing Task

A. *Application of Our Control scheme and Consideration for its Effect in Task Performance*

A model of the motion flow for placing a glass is shown in Fig. 3; the upper figures show how ordinary people execute the task and the lower ones show a professional executes it with active BE contact. The body part that produces the active BE contact is the side of the little finger or the side of the palm. We divide the body parts into two groups according to the new OBE loop produced by the active BE contact: the task executing system includes the wrist and fingers while the bracing control system includes the other parts. After the active BE contact, the two systems are controlled in different control modes. Actuators in the task executing system produce the motion for placing the glass onto table, which is a rolling motion around the BE contact. All actuators in the bracing control system are controlled by a force control method that keeps the force exerted at BE contact at a given constant level.

We were afraid that there might be some uncertainty in this placing task. For example, the actual height of the table might differ slightly from the height in the model or the robot might grasp the glass higher up than in the model. These uncertainties could generate a large collision force at the contact between glass and table. They induce task performance instability. The important point in this task is how to execute it in a short time and how to reduce the contact force between glass and table without fail.

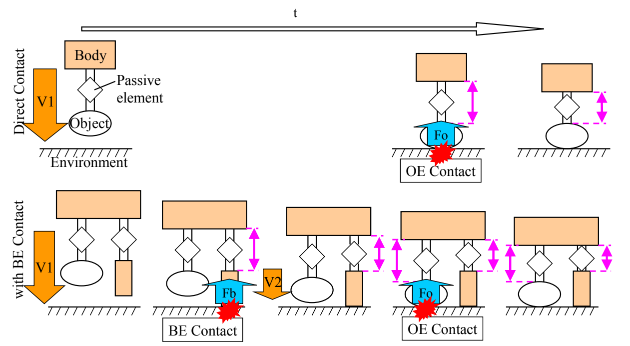


Fig.3. Motion Flow Model for Glass Placing Task

Assuming that the table has a large mass and cannot move, the impact force at contact between the object and environment (OE contact) can be expressed by

$$\int F dt = (e+1)MV \qquad (1)$$

where e is the coefficient of restitution, M is the mass of the object, and V is the approach velocity of the object. This equation shows that the impact force increases in proportion to the approach velocity. Consequently, the previously mentioned two requirements seem to have a trade-off relationship. But our control scheme can solve this problem. In our control scheme, the robot initially makes BO contact at high speed, so only the robot body and not the object receives a large impact force. At the moment of contact, the robot acquires more accurate information about the table height and switches to a slower approach velocity. Thus, this control scheme achieves a short total task execution time and the impact force at OE contact is small.

B. *Explanation of Test Equipment "TWENDY-ONE"*

We used the TWENDY-ONE hand and arm, shown in Fig. 4, as the test equipment. TWENDY-ONE arm is a seven-degrees-of-freedom (7-DOF) redundant manipulator. It has a visco-elastic mechanism with 3 DOFs in the shoulder and 1 DOF in the elbow [12]. Its hand is a human-mimetic hand with three fingers and a thumb with 13 DOFs that can execute 19 kinds of grasping shape like a human. The metacarpophalangeal (MP) joints of the index, middle, and little fingers have mechanical springs. The surfaces of the side and front parts of the fingers and palm are covered with soft material.

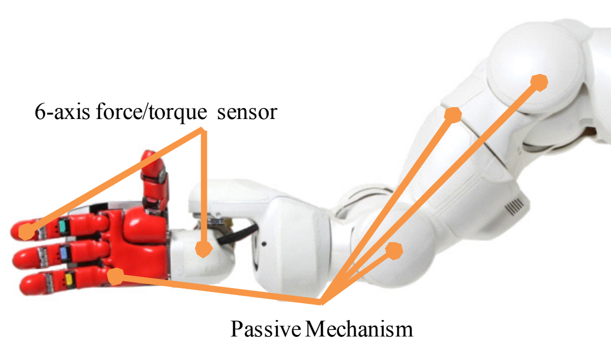


Fig.4. TWENDY-ONE Hand and Arm System

C. Validation Test using TWENDY-ONE

Using TWENDY-ONE, we checked the effectiveness of our control scheme in the glass-placing task. TWENDY-ONE was already grasping a glass having a weight of 150 [g]. It started the approach motion at a position 200 [mm] above the level of the table surface. The approach velocity was 300 [mm/s]. In every test condition, TWENDY-ONE detected the BE contact using the 6-axis force/torque sensor implemented in its wrist and detected the OE contact using the 6-axis force/torque sensor implemented in the tip of its thumb. TWENDY-ONE automatically proceeded to the next sequence. The contact forces at OE and BE contacts were measured with a pedestal force sensor on the table. The test was conducted in three conditions, as described below.

(a) Direct approach (ordinary scheme)
(b) With BE contact with the side part of the palm (proposed scheme)
(c) With BE contact with the side part of the little finger (proposed scheme)

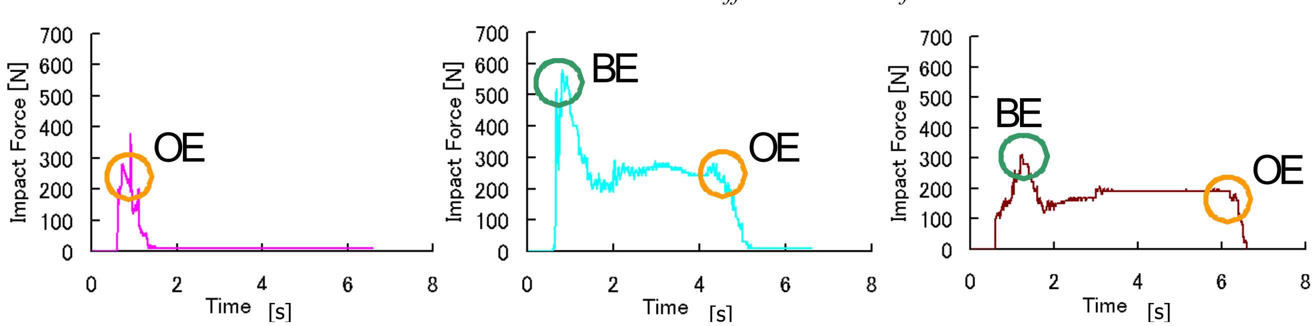
In the condition (a), TWENDY-ONE started its downward motion with grasping the glass, and released the glass when the bottom of the glass made the contact with the table. In the condition (b) and (c), TWENDY-ONE started its motion at the same situation as condition (a). Firstly it made BE contact with its body part and acquired more accurate information about the table height. After that it switched to the slower approach velocity, and made OE contact. The test results are shown in Fig. 5. The x-axis indicates time [s] and the y-axis indicates contact force [N]. The test results are shown in Fig. 5. The x-axis indicates time [s] and the y-axis indicates contact force [N]. The graph for condition (a) has one obvious peak, which indicates that the impact force at OE contact reached about 300 [N]. In fact, a significantly large collision noise occurred in this instance. This large impact force was exerted on the glass. Actually the graphs for conditions (b) and (c) have two peaks for the BE and OE contacts, but we can identify only one obvious peak. This peak indicates the impact force at BE contact. The force measured in the period between BE and OE contacts was exerted by the bracing control system at the BE contact point. Very small peak about 40 [N] at the last second before the reduction of the force on the graph (b) and (c) indicates the impact force at OE contact. These graphs for conditions (b) and (c) show that only a small contact force was exerted on the glass. We could not hear any collision noise at OE contact in these test conditions. From the point of reducing the contact force between the glass and table, we validated that proposed method can improve the performance of this glass-placing task. In conditions (b) and (c), the task execution time was not sufficiently short. This is because we adjusted the motion control of the task executing system to give priority to reducing the magnitude of the contact force. Readjustment should reduce the time without the contact force becoming larger.

In addition, we compared the impact force at BE contact in conditions (b) and (c). The graphs show forces of about 600 and 300 [N] in conditions (b) and (c), respectively. We think that the difference in the impact forces comes from the mass of the body part producing the BE contact. TWENDY-ONE has a mechanical spring in its MP joint, and this spring could decouple the mass of the finger from the other body parts. In condition (c), only the mass of the little finger exerted the impact force, but in condition (b) the total mass of the hand and front arm exerted it. Thus, we conclude that we should select the body part producing BE contact from the perspective of distance from BO contact. A smaller OBE loop is desirable.

From the same theoretical point, we can tell that the impact force at OE contact in condition (a) should be similar to the impact force at BE contact in condition (b), because the mass of the whole manipulator and the glass exerted the impact force at OE contact in condition (a). But the actual impact force in the graph (a) is not so large compared with the impact force of BE contact in graph (b). We thought this is because the slip between the glass and the fingertips was occurred at the moment of this contact. If the grasping force was sufficiently large and hand grasped the glass tightly, this force would be larger and we could validate the effectiveness of proposed scheme from the point of reducing the maximum contact force applied to the table.

IV. Actual Apply Our Control Scheme to Opening Drawer with Magnetic Force Restraint

A. Applying Our Control scheme and Consideration for its Effect in Task Performance



(a) Direct Contact (b) With Palm Contact (c) With the Little Finger Contact

Fig.5. Test Results for Glass Placing Task

A model of the drawer-opening task, which provides a courteous means to open it using active BE contact, is shown in Fig. 6. We divided the body parts into two groups according to the new OBE loop: the task executing system includes the wrist and fingers, while the bracing control system includes the other parts.

As a result, both systems contain the same parts as in the glass-placing task, but their control methods are different. To explain the reason of this difference, we discuss the effect of passivity in this drawer-opening task. In this drawer-opening task, rapid jerky movement of the drawer accompanying the release from the restraint is a problem. It is important to reduce this undesirable movement. If the drawer is restrained by magnetic force, the manipulator must exert a large force to it to release from it from the restraint. In this instance, mechanical springs at hand and arm joint are displaced through a large distance and they store a large amount of elastic potential energy. The mechanical springs release this energy and produce the movement of the end-effector. The movement of the drawer is derived from this end-effector's movement. A mechanical spring with a lower elastic coefficient is displaced through larger distance and can store more elastic potential energy for a given restraint force condition. Thus, the total elastic coefficient of the hand and arm should be larger for high performance in this task. From this viewpoint, we introduce the concept of the resultant elastic coefficient. The number of springs is n, and the nth spring has elastic coefficient Kn. If we connect these springs in series, the resultant elastic coefficient K is given by

$$\frac{1}{K} = \sum_{i=1}^{n} \frac{1}{Ki} \tag{2}$$

This equation shows that if n is small enough or if each elastic coefficient is large enough, K is large. In this paper, we apply the control method to each system, aiming to decrease the number n of the springs which store the elastic potential energy. The actuators in the task executing system produce motion to open the drawer. All the actuators in the bracing control system are controlled by a force control method to cancel the displacement of the mechanical springs installed in the shoulder and elbow joints. As the result of these control methods, the total motion of the hand and arm can maintain the BE contact and open the drawer. During this motion, only the mechanical springs in the task execution system store elastic potential energy, and we can decrease the pseudo number n of the spring in the hand-arm total system. Consequently, the rapid jerky movement of the drawer accompanying the release from the restraint is reduced. From the viewpoint of decreasing pseudo number n, we should make the task execution system smaller. A smaller OBE loop is desirable.

Additionally we were afraid that there also might be some uncertainty in this opening task. The restraint force of the drawer is designed to be a given force level. Although there are differences among the actual individual magnets and magnetic force vary across the ages. Consequently it is difficult to predict how large force is needed to open the drawer with accuracy. However if we apply our motion control scheme to this task, mechanical springs in the shoulder and elbow joint cannot be displaced during the task execution. And so we don't need to concern this problem.

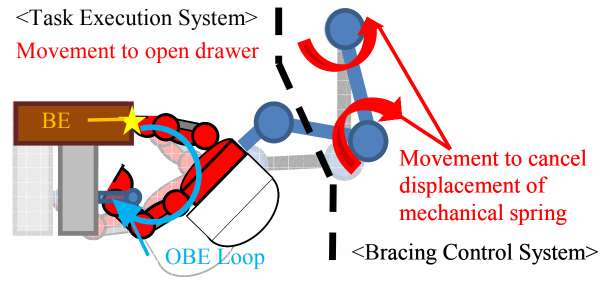


Fig.6. Motion Control Scheme for Drawer Opening Task

B. *Validation Test using TWENDY-ONE*

Using TWENDY-ONE, we evaluated the effectiveness of our control scheme in the drawer-opening task. We chose a drawer normally used in our laboratory and changed the handle to it because TWENDY-ONE's hand is slightly larger than a human hand. This drawer has a magnetic to hold it closed. We replaced the magnet with one producing a restraining force of about 20 [N] to match that of an average refrigerator door. The test was conducted in two different conditions, as described below.

(a) Opening by trajectory control of arm and finger posture is fixed (ordinary scheme)

(b) Opening by finger posture control with BE contact with the thumb finger tip (proposed scheme)

The test results are shown in Fig. 7. The x-axis indicates time [s] and the right y-axis indicates contact force [N] in all graphs. The left y-axis indicates position of the finger tip in the opening direction [mm] in graphs (a)-1 and (b)-1 and displacement of the joint spring [deg] in graphs (a)-2 and (b)-2. The first peak of the contact force indicates the release of the restraint in all graphs. The graph for condition (a) shows that the mechanical springs of the arm were displaced over a large distance by the restraint force and that the position of the finger tip fluctuated considerably after restraint release. The graph for condition (b) shows that the displacement of the mechanical spring was very small and there was no finger tip position fluctuation. This shows that our motion control system produces higher performance for this task.

V. Conclusions and Future Works

We generated coordinated hand-and-arm motion in a humanoid robot to achieve higher task performance. By observing some manual tasks, we identified active body-environment contact as a kind of human manual skill. We proposed a motion control scheme based on active body-environment contact. We applied our motion control scheme to glass-placing and drawer-opening tasks. The test results showed that when our motion control system was applied to TWENDY-ONE, it could can generate appropriately coordinated hand-arm motion and improve the task performance. We think that this trial represents a significant step toward achieving dexterous task execution by human-mimetic hands and arms. It also revealed that passivity has a good effect in the glass-placing task but a bad effect in the drawer-opening task. In both tasks, a smaller OBE loop is desirable. In future work, we are going to investigate other tasks performed using this motion control scheme, and would like to reveal which body part of humanoid we should design to have the passivity from the viewpoint of dexterity using the active BE contact.

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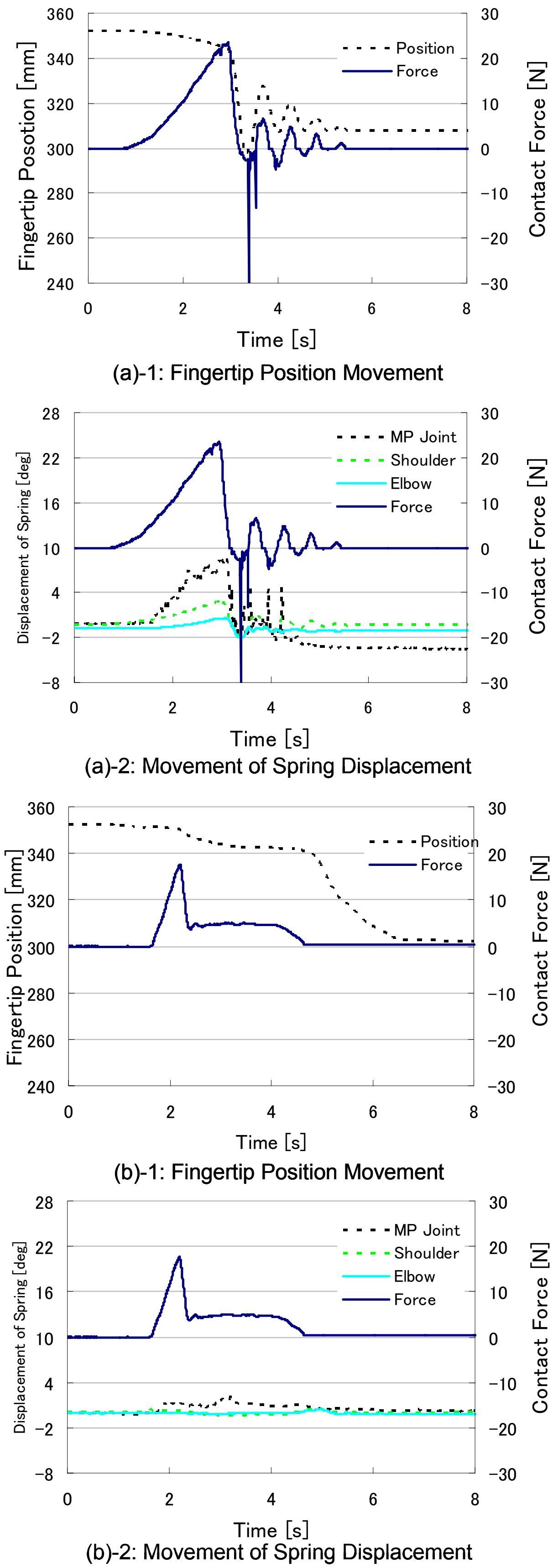

Fig.7. Test Results for Drawer Opening Task