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A Prototype of Index-Finger PIP Joint Motion Amplifier for Assisting Patients with Impaired Hand Mobility

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Abstract— **The authors proposed a methodology of assisting the patients who were suffering from mobility impairment of finger and thumb joints, with exoskeletal devices. The types of exoskeletal assistive devices for such patients were categorized into several groups based on required functions which are derived from the patients' condition. One of the categories, "joint motion compensator" is a novel concept taking into consideration the difference between active-ROM(range of motion) and passive-ROM of joints, and with regard to one of subgroups of this category called "joint motion amplifier", a prototype device which amplifies the motion of index-finger PIP(proximal interphalangeal) joint was constructed and verification experiments for pinching objects were conducted. The results revealed that it was feasible to pick up and pinch objects which were not so small or thin enough to be picked without nails, and also was possible for the device to hold such objects as strongly as human hands do.**

I. Introduction

There are many people suffering from impairment of motor function caused by some diseases. For example, the prevalence of rheumatoid arthritis is of 0.8% adults [15] , and that of osteoarthritis is 10% of the population who are 60 years or older [14]. Impaired motor function makes it difficult to carry out activities of daily living, especially in the case that the loss of motor ability appears at hands and manipulability is limited.

In rehabilitation engineering, which intends to improve or restore impaired motor functions with a device put on part of subject's body, a large number of methodologies and technologies have been studied [12] [16] .

Externally actuated exoskeletal devices, also known as "power-assistance" or "powered-orthoses" devices, which augment the users' muscular power with electrical or hydraulic actuators, also have been developed [4] . Although there are some studies whose targets are finger and thumb joints [10] [13], most of these devices intend to support relatively large joints, such as hip, knee and ankle joints(lower extremities) [1] [3] [5] , or shoulder and elbow joints(upper extremities) [8] [9] [11] .

These devices are useful for impairment of motor function which results from weakened or paralyzed muscles, or damaged nervous systems. However, it is not concerned enough that each of the conventional devices might affect how much load on the joint, or how large the range of motion of the joint is. Therefore, the conventional devices can not work well for mobility impairment with damages on joints or contracted muscles, caused by the diseases such as rheumatoid arthritis or osteoarthritis. And in some cases, the conventional devices even might cause further impairment on the joints.

Hence, the authors propose developing a novel assistive device for the patients with the disorders described above. In other words, we develop an exoskeletal powered hand orthoses helping them with handling objects, taking account of their situation of impairment.

In this paper,we have categorized the types of assistive devices for compensating impaired motor ability of hands, including conventional methodologies, into some groups based on the required functions which depend on the patients' condition and capability of movement. Then, we have constructed a prototype of a joint motion amplifier, one of the classified categories, and have conducted verification experiments for pinching objects.

This paper consists of the following sections. In Section II, requirements for assistive devices with respect to movement disorders of the supposed users will be explained, and a new type of powered orthotic device, "joint motion compensator" will be proposed. In Section III, details of an experimental manufacture of "joint motion amplifier", one subtype of "joint motion compensator", will be described. In Section IV and V, the experimental set-up and the results of pinching experiments with the device will be shown respectively. Finally, we will discuss the results in Section VI and conclude this paper in Section VII.

II. Methodology of Assisting Patients with Limited Joint Range of Motion

A. Active and Passive Range of Motion

When we consider the mobility impairment, the joint range of motion is important measure. In orthopedic surgery, there are two concepts of joint range of motion.

- Active range of motion(Active-ROM).
- Passive range of motion(Passive-ROM).

"Active-ROM" denotes the range of motion in which the subject can move the joint by themselves at will, and "Passive-ROM" means the range of motion in which the joint can be moved externally. Naturally, passive-ROM is leager than active-ROM. As shown in next subsection, it is important to distinguish these two ROMs when we consider assisting the patients with mechanical devices.

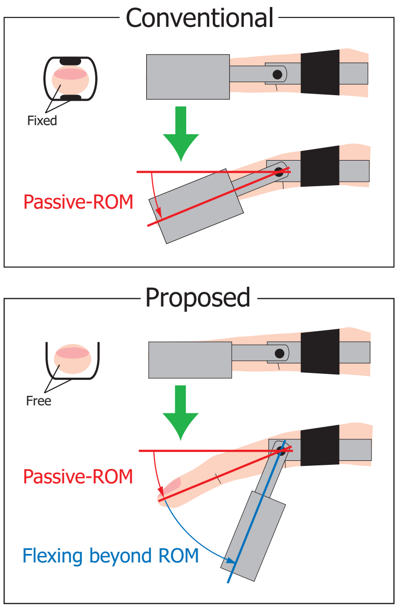

Fig. 1. Concepts of a conventional exoskeletal device(top) and a proposed "joint motion compensator"(bottom).

B. Necessity of Joint Motion Compensation

Here, compensation of limited ROM is discussed in detail. In what follows, "to pinch" denotes handling relatively small objects only with fingertips, and "to grasp" represents handling relatively large objects with fingers' palmar side not only of distal segments but also of proximal segments and, in some cases, with a palm. Unless otherwise stated, both types of prehension includes "manipulation" in a narrow sense, which allows relative movement between the hand and object durinig handling.

As described in previous section, most of the motion support devices don't intend to recover the joint function primarily. From the viewpoint of improving ROM using the devices, a subject can regain active-ROM, and augment pinching and grasping force, within the bound of passive-ROM. In other words, the devices work well only if passive-ROM is not limited, or the limitation is little. Therefore, it is impossible for the devices to reduce the difficulties caused by the inadequate passive-ROM. For example, a user of the devices can not pinch a small object with flexing a finger and thumb beyond the passive-ROM, or, conversely, grasp a large object with extending them in the same way. In the worst case, if the devices flex or extend in excess of the user's passive-ROM, it might cause further damages on the joint.

For these reasons, for the purpose of assisting the patients with the joints whose passive-ROM are limited, a novel methodology is required which compensates the lost passive-ROM without enforcing the joint to flex or extend beyond the ROM. As a means of realizing this methodology, we propose "a joint motion compensator", a new type of powered orthoses as shown in Fig. 1 .

The joint motion compensator works in the following way. While not pinching or grasping an object, the device's finger covers user's finger, and both of them are in closely contact. When the user is going to pinch or grasp the object, the device's finger leaves user's hand and flexes beyond the ROM depending on the target finger joint angle and/or the fingertip force, or motion of another part of user's body, or myoelectric signals and so on.

The joint motion compensator contains a mechanism which operates as substitute for user's finger or thumb. It is desirable that the axes of the devices' joints correspond to that of the fingers' and thumb's joints. This makes it possible to simplify the control law of the device, and allows users to operate them intuitively.

C. Categorizing Assistive Devices

The assistive devices for the patients with impaired hand motion, including both conventional ones and proposed one, can be divided into some categories based on required functions which are derived from the patients' condition or capability of movement, as shown in Fig. 2 .

The details of each category are as follows.

1) Joint Protector: The purpose of the devices in this category is to protect the target joint by lessening loads on it, during pinching or grasping an object. Although this can be accomplished by conventional orthoses to some extent, it is difficult for them to keep maneuverability simultaneously. Hence, we suggest an idea for implementation of the joint protector, which maintains the workability.

The device operates like this: When not in use, the device has the joint locked and it works as an immobilizing brace for the fingers. During pinching or grasping motion, the device's joint is unlocked and enables the fingers to flex, then it is locked again with the fingers holding an object. The actuators are used only to change the status of the joints of the device.

Note that the type which is specialized in protecting joints is described here, though the devices in the other categories also contain this function,

2) Externally Actuated Exoskeletal Devices: This category is the same as the conventional externally actuated exoskeletal devices ("power-assistance" or "powered-orthoses") listed and described in Section I .

3) Joint Motion Compensator: This is the proposed methodology. The structure of the device is as described in above subsection and Fig. 1 . In addition, the devices can be divided into two groups further, on the basis of inputs.

a) Joint Motion Amplifier: This method's targets are patients whose active-ROM are remained, even they are a little, and they can flex or extend the joints within the range. Thus, the device utilizes the information of the target finger's motion(angle of the joint and/or force at the fingertip) within the limited active-ROM, as inputs, and puts out amplified motion with the device's fingers.

b) Joint Motion Replacer: This is for the patients whose passive and active-ROM are both very little. In such cases, the motion of the target finger can not be utilized as inputs. Therefore, other information, such as motion of another part of user's body, or myoelectric signals should be

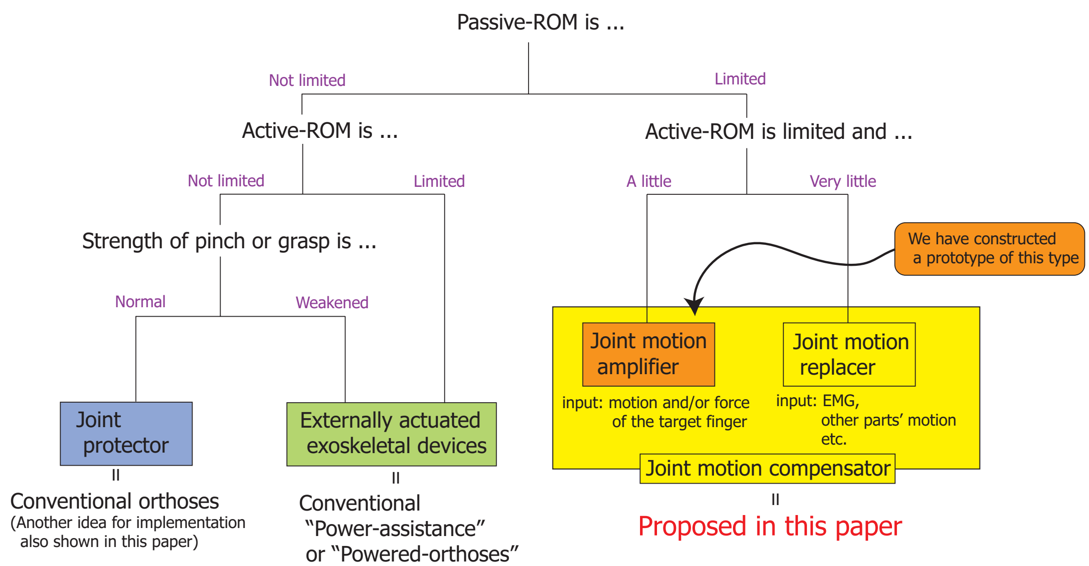

Fig. 2. Categorizing the types of assistive devices based on required functions depending on the patients' condition or capability of movement.

used instead. Since the device's motion have no relation with the target's, we name this "motion replacer".

Note that the joint motion compensators can be also used to amplify the strength of pinching or grasping. The difference between conventional devices and them is whether they can work beyond user's passive-ROM or not.

To explore the feasibility of pinching objects without narrowly-defined manipulation using the "joint motion amplifier", we constructed a prototype and conducted some experiments with that. In the following sections, the details of the trial manufacture and the experiments will be shown.

III. Trial Manufacture of the Index-Finger PIP Joint Motion Amplifier

In daily living activities, among prehension patterns without manipulation in a narrow sense, pinching with a thumb, index-finger and long-finger is observed very frequently [6]. Thus, we aim to realize this pinching pattern. On the occasion of design a prototype device, we intended to achieve the pinching with the simplest composition at the beginning. In consequence, the prototype consisted of 1 DOF index-finger and fixed counterpart of it, and the input for the system was user's joint angle.

The appearance of the amplifier and its components are shown in Fig. 3 . A mounting is made of thermoplastic plastic which is used for orthoses. Weight of the whole of the part attached on user's forearm is approximately 350 g. Electric power is supplied externally with cables, and a controller is separated and connected with wires. The controller is also linked with a PC, which sends commands for changing operation modes of the device, commands for changing some settings such as amplification gain, and records the data.

The amplifier is an exoskeletal structure covering the lateral and palmar sides of an index-finger. It contains a 1 DOF index-finger, which has a joint whose position corresponds to user's index-finger's PIP(proximal interphalangeal) joint. As a counterpart of the index-finger, an aluminum plate, with a piece of silicon rubber on its surface for slip resistance, is fixed to the device. This is for the reason that we intend the subjects not to use their thumb during the experiments, in order to prevent the mobility or tactile sense of their thumb from compensating the device's workability. When in use, the device is attached to the forearm and dorsal side of the hand of the user. Note that this prototype is designed to be easily constructed, since its main purpose is to verify the feasibility of assistance with such kind of devices. Hence, it is rather heavy and cumbersome and there is room for improvement, for example, by miniaturizing the motor and sensor, or by using lighter materials. In addition, although the device can be attached to a healthy user within a minute, it might be difficult for the patients to wear it by themselves. This problem must be solved in further development process.

The details of each component will be described in the following subsections. And at the end of this section, a process of amplifying joint motion will be shown.

A. 1 DOF Index-Finger

The mechanism and motion of the device's index-finger are shown in Fig. 4 . To flex device's joint, we adopted a link mechanism. The small DC motor put on the dorsal side of the hand reels the driving wire, which pulls the end of the link and drives the mechanism, as shown on the left side of Fig. 4. Since the wire can only flex the joint, extensor springs are inserted, and the joint returns to be extended automatically when the wire is loosened. The range of motion of device's fingertip is set from 30 degrees to 75 degrees, with respect to the extended position and positive for the direction of flexion. Maximum pinching force is approximately 10 N.

To measure the angle of device's joint, an angle sensor was put directly beneath the joint. The sensor utilizes a strain gauge adhered on a thin stainless steel sheet whose thickness

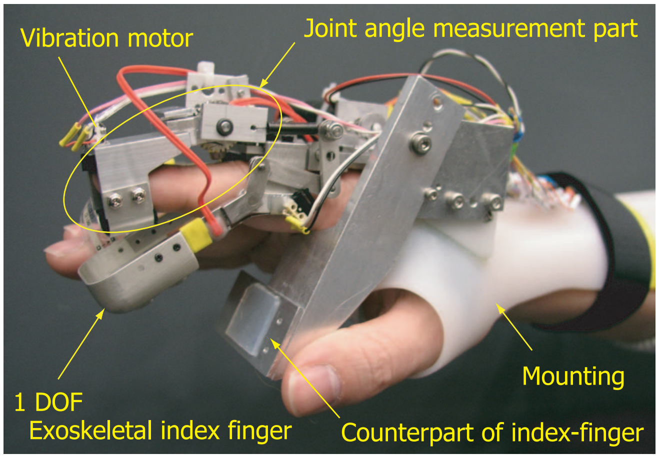

Fig. 3. Overview of the index-finger PIP joint motion amplifier.

is 0.1 mm. With one end being fixed to the base of the device, the sheet works as a cantilever. In the case that the joint flexes, device's fingertip pushes the free end of the cantilever and makes it bent, inducing change of the resistance of the strain gauge. Thus, the joint angle can be measured indirectly through the value of the resistance.

On the fingertip of the device, pressure sensors(Tekscan Inc., "FlexiForce$^{\text{TM}}$") are installed to detect the contact with objects and measure the strength of pinching. For slip resistance, a piece of silicon rubber is attached to the surface of the sensors.

B. Joint angle measurement part

This component contains a joint angle sensor for measuring the angle of user's finger joint, whose principle of measurement is the same as the sensor at the device's joint. The range of motion of user's finger is set from 0 degree to 30 degrees, with respect to the extended position and positive for the direction of flexion.

In addition, to feedback the contact sensation to user's finger, as described later, a small vibration motor is set on the component(see Fig. 3) .

C. Controller

Control processes including the servo loop of the DC motor are handled with a microprocessor(Renesas Technology H8/3052). With the controller, amplification of the motion of index-finger's PIP joint is realized. The right side of Fig. 4 shows the sequence of the amplification with 2.5 times. This is performed through following process: first, index-finger's angle is measured with the angle sensor, then the product of the angle value and amplifier gain is set to the goal value of device's servo loop of the motor. Although the cycle of this process varies depending on the communication traffic, it is not less than 50 Hz.

The device has the following three operation modes.

1) Without amplification:
Device's fingertip can be moved freely, irrespective of user finger's position, with the fingertip cover being pushed by a user directly. (This mode is used to obtain reference data for comparing those of the other modes during experiments.)
2) Joint motion amplification based on angle input without contact sensation feedback:
User's joint motion is amplified with the method described above.
3) Joint motion amplification based on angle input with contact sensation feedback using vibration:
The same as previous one except that the vibration motor works when the fingertip of the device touches an object, and the user can obtain information on the condition of contact.

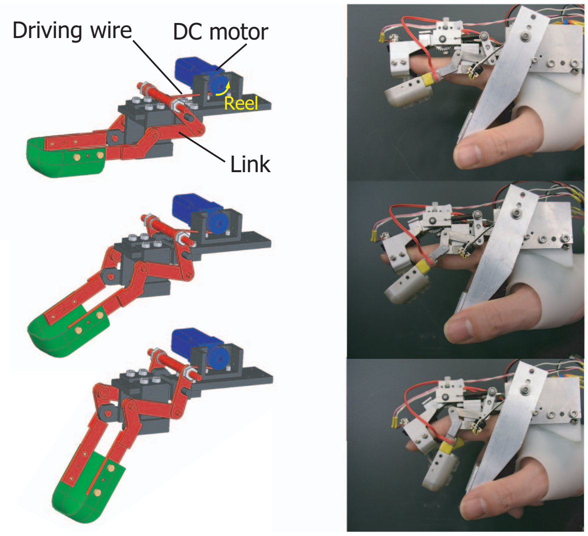

Fig. 4. Device's link mechanism(left) and sequential photographs of device's motion during 2.5 times amplification(right).

IV. Experiments of Pinching Objects

To investigate the feasibility of pinching objects with the joint motion amplifier, and to reveal the problems for further development, we conducted some experiments.

Seven objects listed on Table I were used for the experiments. The experimental task was to pick one object on the surface of a desk at a time from the start area and place it at the goal area which was 300 mm away, with dominant hand(the start and goal area are both 80 mm square). Measured values through the experiments were; time needed for completing the task, joint angle of the user and device, and fingertip force of the device. These data were obtained and recorded at 50 Hz.

The task was tried with three different operation modes of the device described in the previous section, in the following order: 1) without amplification, 2) joint motion amplification based on angle input without contact sensation feedback, 3) joint motion amplification based on angle input with contact sensation feedback using vibration. Amplification gain was fixed as 2.5, which was led from the ratio of the range of the joint angle measurement part to that of the exoskeletal index finger. The device is attached to user's forearm and hand, and this restricts kinesthetic and tactile sense considerably. Thus, it is desirable that some mechanisms which supplement the

TABLE I

OBJECTS USED IN THE EXPERIMENTS.

No.	Object	Shape	Measurements(mm)	Mass(g)
I	Dry battery(006P)	cuboid	(D)25 × (W)45 × (H)16	41
II	Wooden ball	sphere	ϕ20	3.2
III	Dry battery(AA)	cylinder	ϕ14 × (W)50	26
IV	DV tape	cuboid	(D)73 × (W)52 × (H)16	37
V	Glue(stick-shaped)	cylinder	ϕ25 × (W)100	30
VI	Cube sugar	cube	(D,W,H)15	3.7
VII	Weight	cylinder	ϕ20 × (H)18	50

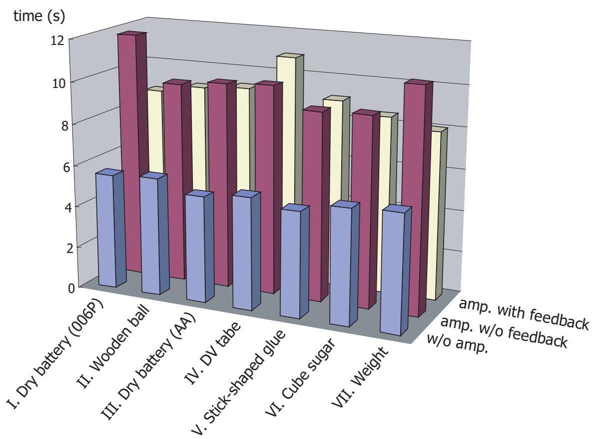

Fig. 5. Average time needed for completing the tasks with respect to each object.

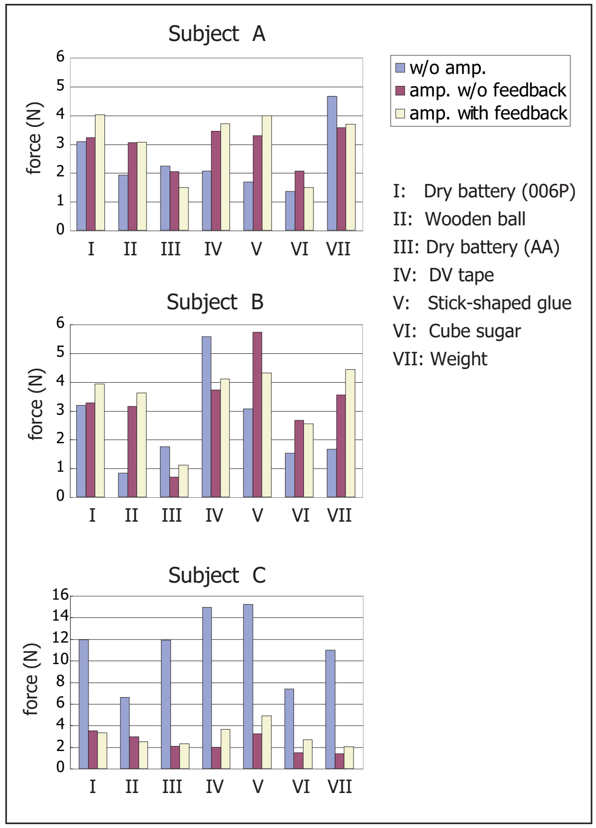

Fig. 6. Fingertip force during pinching objects(time average).

lost sense are equipped. Contact feedback with vibration had been expected to be one of such option and contribute for improving workability with the device. Therefor, to study the effectivity, we conducted the third trial.

All of the objects were not so small or thin relatively. This is why it had been expected to difficult to pick up such objects from the surface of the desk, because of the interference between the desk and the device's fingertip. To pick up objects from a flat surface is a difficult problem and some researches dealing with this are ongoing [7] . Once again, the prototype device was designed to be uncomplicated structure for simplifying construction. It has only 1 DOF and the possible position and attitude of the fingertip were restricted. And we had judged that it was not essential for the prototype to be able to pick up such objects, even though the function would be needed for practical use. Therefore, small or thin objects were eliminated from the experiments.

V. RESULTS

The number of subjects were three, all of them were male and in their 20s, who were not with mobility impairment in their hands. All subjects' dominant hand were right. The subjects' ROM(both active and passive) were restricted by the device's angle measurement part, therfore, a situation where patients use the device could be simulated. To get accustomed to the device, the subjects were told to operate it for a couple of minutes without pinching objects before the tasks. The number of trials for each object was one.

Fig. 5 shows the average time needed for completing the tasks with respect to each object, which includes time for approaching to the object from the initial position, pinching and picking up, moving towards the goal and releasing. It is clear that "without amplification mode" took less time than the others. Two "amplification mode" required no more than 12 seconds. The worst time for all "amplification mode" trials was 14.4 seconds, which was recorded in the case of pinching the weight with "amplification without feedback mode". Comparing two cases with and without contact sensation feedback, it turns out that less time is spent for accomplishing tasks with the feedback slightly. However, since the difference is not so significant, we can not judge from only these results whether the contact sensation feedback is effective or not for improving operability.

Fig. 6 shows time average of force at device's fingertip during pinching objects. With regard to the subject A and B, comparing to "without amplification mode", the force measured in two "amplification mode" was greater or almost the same in many cases. Although the subject C tended to pinch much stronger than the others, the force in both "amplification mode" was not extremely less than that of the other two subjects. These results demonstrate that objects can be held using the device in both "amplification mode" with a certain level of strength, which is, at least, greater or almost the same measuring against the strength in "without amplification mode". In other words, even though it depends how to hold an object between the index-finger and thumb, the device is able to pinch object as strongly as human hands do. Again, we can not detect any meaningful difference between the cases with and without contact sensation feedback.

VI. Discussion

It turned out that some objects, not so small or thin, were able to be pinched with the prototype of the joint motion amplifier, and derived prospect that the device could assist the supposed users. At the same time, it revealed the following problems.

Firstly, the contact sensation feedback should be modified. Judging from the experimental results, the sensation feedback mechanism with the prototype device does not work effectively. Actually, the subjects completely relied on seeing an object to figure out if it had been held or not. However, such mechanism supplementing the restricted kinesthetic and tactile sense is required to be installed, not only to improve operability, but also to handle soft or fragile objects. Thus, modification of the sensation feedback mechanism should be continued.

Secondly, it is necessary to examine how the motion of a thumb can be realized by an assistive device. Although the prototype has only one joint in the index-finger, to apply the device to the patients actually, there need to be several joints allocated depending on each patient's condition. The movement of a thumb facing fingers oppositely is very important for pinching especially. In this study, a thumb was substituted with the fixed part. If the motion of a thumb is also performed by the joint motion amplifier, it is not apparent whether pinching objects can be completed or not.

Thirdly, the finger mechanism have to be improved in order to handle smaller or thinner objects. Concerning the degrees of freedom, the larger number of them, the more kinds of objects can be pinched and the more work can be done in general. However, there is a trade-off between the degrees of freedom and the complexity of the device. Therefore, a methodology of evaluating merits and demerits of addition of the degrees of freedom quantitatively, should be established. To handle more kinds of objects, device's fingertip also must be upgraded. The shape, structure(including nails) and material can be modified referring to many related research works in robotic hands [2].

VII. Conclusion

In this paper, we proposed a methodology of assisting the patients, who were suffering from mobility impairment of finger and thumb joints, with exoskeletal devices. The types of exoskeletal assistive devices were categorized into three groups: 1) joint protector, 2) externally actuated exoskeletal devices, 3) joint motion compensator, based on required functions which were derived from the patients' condition or capability of movement. The third category, "joint motion compensator" was a novel concept taking into consideration the difference between active-ROM and passive-ROM of joints. And this was further divided into two groups: i) joint motion amplifier, ii) joint motion replacer, from the basis for the kinds of an input to the device. Among these categories, a prototype device of "joint motion amplifier" which amplifies the motion of index-finger PIP joint was constructed, and verification experiments for pinching objects were conducted. The results showed that it was able to pick up and pinch objects which are not so small or thin enough to be picked without nails, and also was possible for the device to hold such objects as strongly as human hands do. The experiments also revealed some problems to be solved for further development. Concretely, to develop a mechanism which provides kinesthetic and tactile sensation effectively, to examine how thumb's motion can be realized by an assistive device, and to improve the finger mechanism concerning the balance between the workability and the device's complexity.

In the future works, the clarified problems through the experiments should be solved. In addition, development of the assistive devices in the other categories will be advanced.

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