DEVELOPMENT OF ORAL-REHABILITATION ROBOT

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***Abstract*— It is well known that the massage therapy is useful for the rehabilitation of various diseases (i.e. oral health problems, etc.). Although various apparatus have been developed for the massage of the torso and limbs, there is still little knowledge about their real effectiveness. However; thanks to recent advances in robot technology (such as actuators, sensors, control system, etc.), more effective advanced tools to provide massage therapy can be conceived. For this purpose, authors have proposed the development of a robotic system that provides massage therapy as an advanced evaluation tool to determine objectively the effectiveness of the therapy. In particular, a novel rehabilitation robot has been designed to provide massage of the maxillofacial region as a therapy to patients with dry mouth, etc. As a result of our research, in this year, we have succeeded in developing the Waseda-Asahi Oral-Rehabilitation No.1 (WAO-1). WAO-1 is composed by two 6-degree of freedom arms with plungers attached at their end-effector. In order to provide the massage, a virtual compliance control has been implemented to control the positioning and the applied force by the plunger. Preliminary experiments were carried out to confirm the effectiveness of the proposed system. In particular, WAO-1 was programmed to provide massage on two tissues: parotid gland and masseter muscle. From the experimental results, we could detect the effectiveness of stimulating the production of saliva, and increasing the skin temperature as well as the size of masseter muscle on volunteers after providing the massage with WAO-1.**

I. INTRODUCTION

The expected aging of society in Japan will undoubtedly increase the needs of medical and dental treatment and rehabilitation. Due to the increase need of medical care for patients and elderly persons, more trained experts and financial resources are required for providing services effectively. This causes a big problem for the both government and hospitals. Therefore, it becomes necessary the introduction of advanced tools designed for providing treatment to patients and elderly persons. As an approach for the introduction of robotic technology to dentistry, we have proposed in 1986 at Waseda University the concept of "dental robotics" ([1-2]). Such concept was based within the framework of cooperation between engineers and medical workers. The concept of "dental robotics" is based fundamentally in the following two points:

1. In the physiotherapy, treatment procedures by means of robotic systems enable to evaluate the efficacy of the treatment objectively. In contrast, it is difficult for conventional manual treatments to compare between the subjective strength of stimulation and effectiveness. Because the conventional manual manipulation is based on the experience and intuition of experts.

2. Develop a new physiatrist manipulation technique that is taking advantages of robot system. Robotic physiatric manipulations bring solution to cope with the increased demands of therapy by expert physiatrician.

Other examples of robotics systems for rehabilitation purposes have been proposed [3-6]. However, none of them has been designed to provide therapy massage for patients with oral health problems. In Japan, the estimated prevalence of oral health problems such as dry-mouth, temporomandibular joint (TMJ) and swallowing are estimated to be over ten million persons. In order to reduce the symptoms from those diseases, patients receive massage therapy to specific target organs; such as masticatory muscles and salivary glands.

Based on our experience on developing dental robotics, we proposed the development of a new rehabilitation robot designed to provide massage therapy of the maxillofacial region. Therefore; in this paper, we are presenting the Waseda-Asahi Oral-Rehabilitation Robot No. 1 (WAO-1), which is composed by two arms (each with 6-DOFs) and plungers attached to the end-effectors in order to provide effective massage to patients. Furthermore, the details of the control system and safety features of WAO-1 are introduced. Finally, in order to confirm the effectiveness of WAO-1, an evaluation experiment was conducted.

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II. Maxillofacial Massage Therapy for Patients with Dry Mouth

The disease of dry mouth, also known as *Xerostomia*, is characterized by an abnormal dryness of the mouth due to the reduced capability of the patient to produce saliva. Such condition can be provoked by several reasons, such as diabetes mellitus, kidney diseases, stress, drugs, etc. The main symptoms are dehydration, pain in the oral cavity, and the abnormalities on the sensation of tasting. In severe cases, patients complain about difficulties to swallow and even to speaking. Nowadays, the pharmacotherapy and physiotherapy are the main procedures of treatment to patients for stimulating the production of saliva. In addition, dental treatment and physiotherapy are also provided [7].

For better understanding of the maxillofacial massage, we mention about the human anatomy. The saliva is produced mainly from three sorts of glands: sublingual, submandibular and parotid. In general, the maxillofacial tissue massage is provided to the parotid gland due to its great contribution on the production of saliva (Figure 1).

The therapy treatment consists of providing massage to the parotid gland and its excretory ducts in order to stimulate the salivary flow. The massage includes the both petrissage and effleurage manipulation techniques. The petrissage manipulation is useful to stimulate the specifically target organ directly. The effleurage manipulation provides indirect stimulation by rubbing the skin surface.

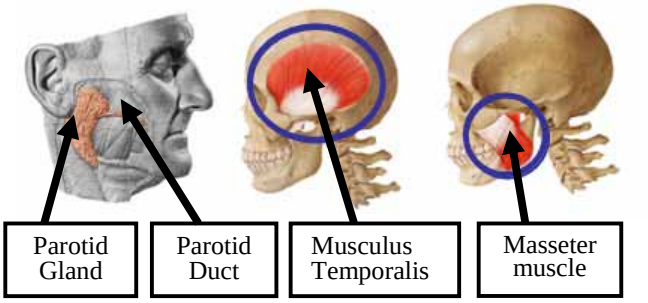


Fig. 1. Maxillofacial tissue massage consists on providing stimuli around the parotid gland, musculus temporalis and masseter [4].

III. System Description

A. Design Concept

In order to provide effective massage to patients, the development of WAO-1 is based on the following design specifications:

1) Working Area: As we described previously, the target organ of the massage therapy for dry mouth is parotid gland. Similarly, temporal and masseter muscle are deemed as the target of massage for TMJ disorders. Therefore, the working area of WAO-1 should be designed to include above anatomical structures, as shown in Figure 2.

2) Mechanism: In order to perform massage on both Zone A and Zone B, the WAO-1 mechanism should consist of two-arm manipulators that are utilized to control the position/orientation of plunger devices (attached to the end-effector). Of course, it is desirable that the driving mechanism of the arms is located out from the patient's visual field.

3) Applied Force: Using a head model that we will describe later, we measured the dynamic force on patient's head during the massage of maxillofacial region by skilled physiatrician. Thus we defined a maximum force of 4 [kgf] to massage around patient face. Therefore, WAO-1 designed to apply the same force to physiatricians.

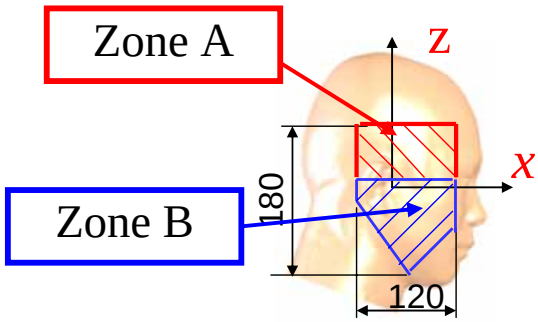
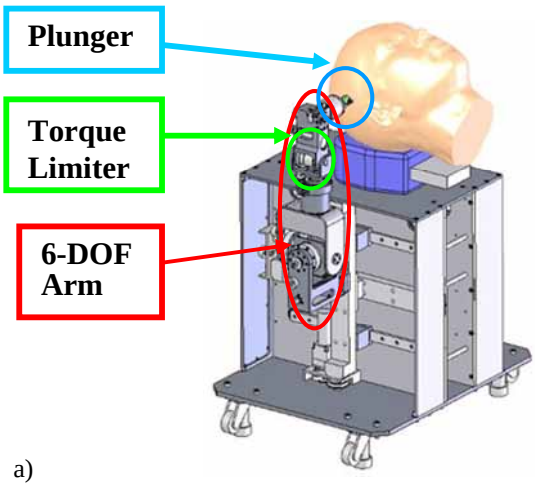
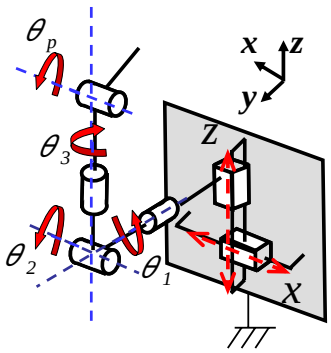


Fig. 2. Musculus temporalis is defined as zone A and parotid gland and masseter are defined as zone B.



a)



b)

Fig.3. System configuration of WAO-1: a) WAO-1 is composed by two 6-DOF arms and plungers. The torque limiters were attached in the arm middle part as safety device; b) DOF configuration of one arm
arm

B. System Description

The mechanism of WAO-1 consists of two main parts: robot arms and the plunger device. Robot arms consist of two 6-DOF manipulators used to control the movement of the plunger device attached to the end-effector of each manipulator. The plunger device is the only part of the robot having direct contact with the patient face (Figure 3a). In the following paragraphs, a more detail description of each of the parts of WAO-1 will be provided:

1) Robot arms: Each of the arms of WAO-1 is composed by a 6-DOF manipulator (Figure 3b). Each arm consists of two translational DOF on the base and four rotational DOF at the each joint of the arm. Due to this DOF arrangement, the robot arms do not obstruct the patient's field of view while providing massage. Each translational DOF consists of a ball screws and a DC servo motors which assures high positioning accuracy. Each rotational DOF consists of a harmonic drive gears and a DC servo motors with no backlash.

2) Plunger: A plunger which applies force to the facial tissues is located at the end-effector of each arm. We have designed different kinds of plungers by changing their shape, material, and number of passive degrees of freedom. Such plungers are exchanged easily depending on the needs of the kind of massage (Figure 4).

3) Safety Device: The WAO-1 has been designed to applied force to facial tissues of patients. Therefore, we require considering safety features that are needed to avoid as much as possible any possible risk to the patient. For that purpose, we have proposed the safety system shown in Fig. 5. As it can be observed; at first software limiters and watch dog timer are implemented into the control software of the robot. In particular, rotational speed and motion positioning are limited within safety range of operation. The second safety feature has been implemented by attaching limit sensors at each DOF as well as fuses to limit the current supplied to each motor. The third one is implemented through torque limiters. The torque limiter has been placed in the middle part of each arm. In the case that the plunger load exceeds a threshold value; even if the robot system presents an unexpected failure meanwhile applying force on the patient's face, the arm will bend and the load will be also released to avoid any injury to the patient (Figure 6). Finally, the fourth and fifth safety features enables to the doctor and the patient to stop the operation of the robot at any time in case of emergency.

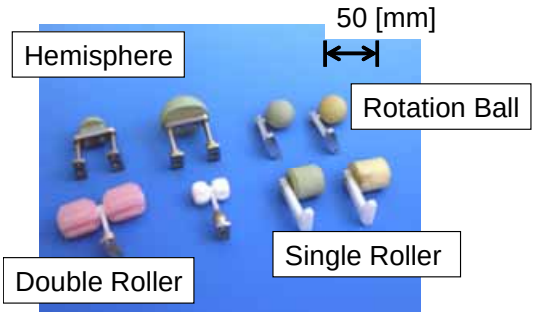


Fig. 4. Several types of plungers; which are fixed at the end of the 6-DOF arm

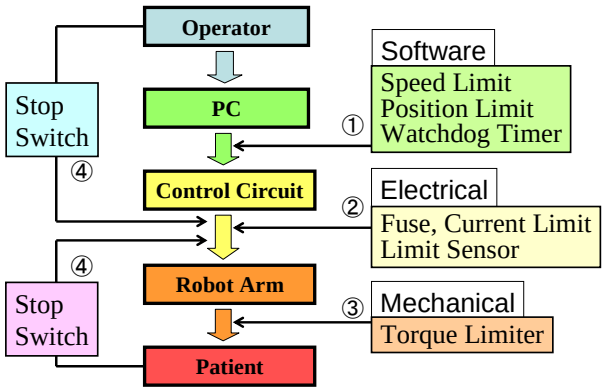


Fig. 5. Outline of safety system. WAO-1 is equipped with different kind of safety features. The safety devices are implemented by software, electrical and mechanical means.

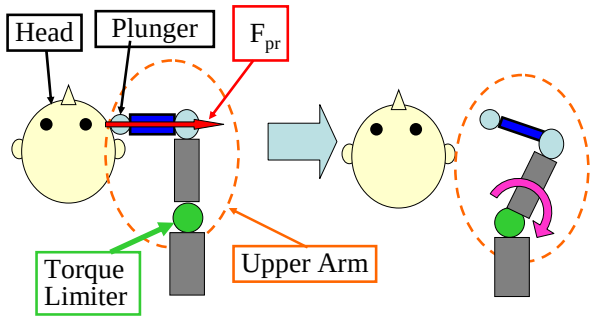
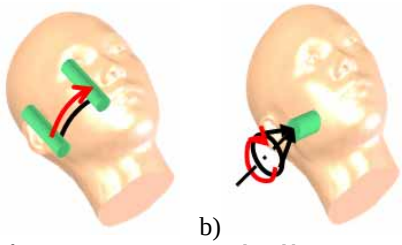


Fig. 6. Torque Limiter principles: a) when $F_{pr} < F_{th}$ is found, the applied force is transmitted through the torque limiter, b) when $F_{pr} > F_{th}$ is found, the applied force is disabled.

IV. Control System Description

In order to control the motion of the plungers attached at each arm of WAO-1, a position control system is implemented. Basically, WAO-1 provides two kinds of massages, one is "effleurage" and the other is "petrissage" [9]. The methods of these massages are shown in Figure 7. "Effleurage" massage is a technique that rubbing the face along the vassals (i.e. blood vessels, parotid duct, muscular fiber, etc.). On the other hand, "Petrissage" massage is used to provide physical stimuli around the maxillofacial tissues (i.e. masticatory muscles, parotid gland, etc.) with rotational movements.



a) b)

Fig. 7. Types of massage movements reproduced by WAO-1: a) effleurage and b) petrissage.

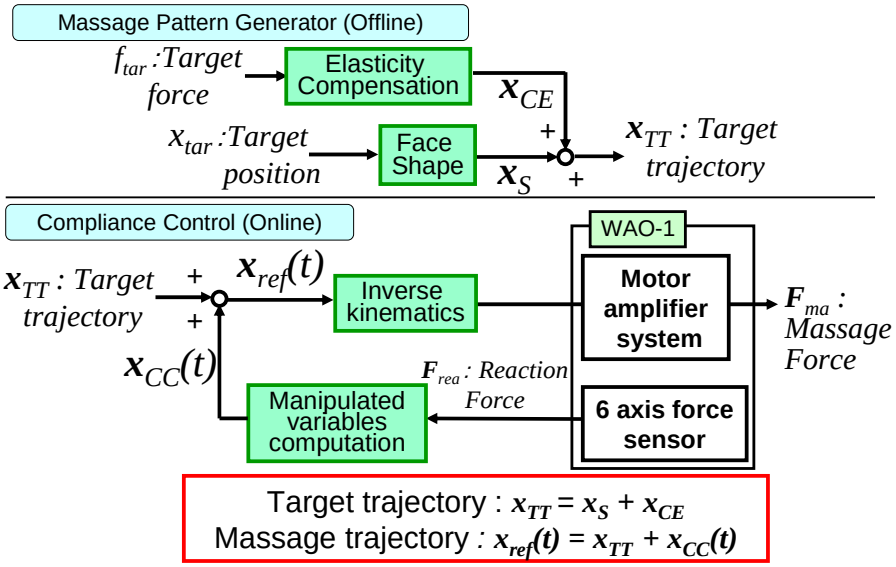


Fig. 8. Block diagram of the control system of WAO-1

The block diagram of the control system of WAO-1 is shown in Figure 8. Basically, in order to provide the massage by WAO-1, the control system is composed by a Massage Pattern Generator and Compliance Control.

Regarding the massage pattern generator, the target massage trajectory x_{TT} is calculated before the massage treatment. The target massage trajectory is calculated with the CT image of human face and the elasticity model of it. The facial surface line x_S is calculated with CT image of a human face as shown in Figure 9. On the other hand, the amount of elasticity compensation (x_{CE}) is calculated with the elasticity model of human face. This model is obtained by a experiment. Therefore the target trajectory (x_{TT}) is generated based on x_S and x_{CE} in offline. In order to compensate for face shape model error, x_{ref} is then calculated based on x_{TT} and x_{CC} in online.

The facial surface line is calculated with the CT image of human face. The doctor chooses 6 point of the facial surface on the CT image and the facial surface line Xs as a spline curve fitting these 6 points is calculated. the amount of elasticity compensation (x_{CE}) is then computed to give the target force (F_{tar}) to facial organs. The target force is determined by doctor. By using such a value, we compute the amount of elasticity compensation (x_{CE}). The relation between the F_{tar} and x_{CE} has been experimentally obtained.

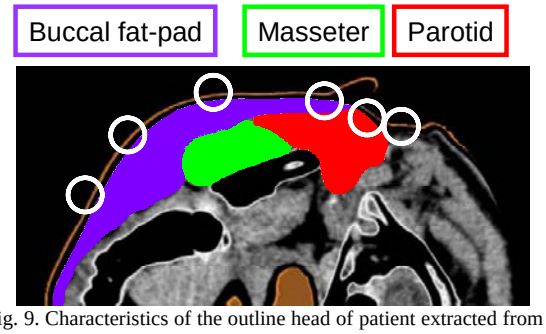


Fig. 9. Characteristics of the outline head of patient extracted from a CT image (horizontal cross section).

The compliance position of the plunger (x_{CC}) is then calculated from the applied forces (F_{rea}) measured through the 6-axis force sensor. In order to determine the compliance position of the plunger, we used the virtual compliance control law defined as (1). As we may observe, the virtual compliance control is done by computing the actual position based on the reaction forces, assuming that a robot has virtual spring and damper elements [10]. Then, by using (2), the discrete value of x_{CC} can be computed.

Thanks to the implementation of the virtual compliance control, WAO-1 is able of assuring the stability of the motion of the plungers along the actual facial shape of the patients (Figure 10).

$$\mathbf{F}_{rea} = \mathbf{K}\mathbf{x}_{CC} + \mathbf{C}\dot{\mathbf{x}}_{CC} \qquad (1)$$

$$\mathbf{x}_{CC}(t) = \left(\mathbf{K} + \frac{\mathbf{C}}{\Delta t}\right)^{-1}\left(\mathbf{F}_{rea} + \frac{\mathbf{C}}{\Delta t}\mathbf{x}_{CC}(t-\Delta t)\right) \qquad (2)$$

F_{rea}: Force/Moment vector
K: Virtual spring matrix
C: Virtual viscous matrix

V. Experiments And Results

A. Massage Therapy of the Parotid Gland

An evaluation experiment of WAO-1 is performed. In this experiment, WAO-1 provides the massage to 6 healthy volunteers (without any maxillofacial disorders). Each subject is provided the massage to its parotid gland for 2 minutes.

In order confirm the effectiveness of the massage provide by WAO-1, the production of saliva was considered as performance index. This index is measured by using the Saxon test [11]; which is a standard method to confirm the effectiveness of the massage therapy. In this test, gauze is put

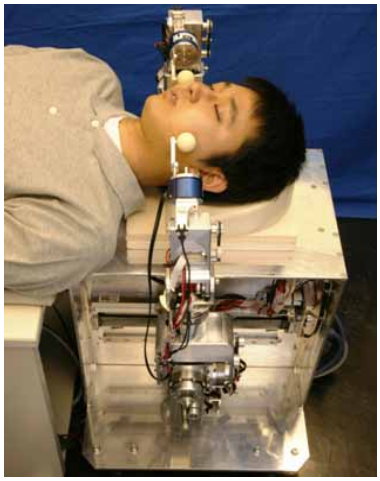


Fig. 10. Screenshot of WAO-1 while providing massage therapy

into subject's mouth for two minutes, and the weight of saliva is then measured. The massage experiment is conducted by the following flow.

1. The subject lies and put his / her head on the robot to receive the massage for 5 minutes.
2. After 5 minutes rest, the Saxon test is performed for 2 minutes.
3. The subject rest for 5 minutes.
4. The massage for parotid gland is provided and Saxon test is performed.

The experimental results are shown in Fig.11. As we can observe, the average production of saliva was increased by 0.63 [g] after providing the massage. By analyzing the collected data with a t-test, we found a significant difference ($p < 0.05$). Thus the effectiveness of the massage to the parotid gland by WAO-1 is confirmed. On the other hand, when the doctor gives the massage to the parotid gland of the people, production of saliva increases 1.4 [g] (average of 6 people). Therefore, the effect of WAO-1's massage is less than that of doctor's massage.

B. Therapy Massage of Masseter Muscle

WAO-1 provides the massage to 11 healthy subjects (without any maxillofacial disorders). In this experiment, WAO-1 provides massage to masseter muscle for 2 minutes. During these 2 minutes, the massage is provided to the upper part of the masseter muscle and the lower side of the masseter muscle. The skin temperature and size of masseter is measured before and after the massage. Skin temperature is measured by the thermal camera before, just after, 10 minutes after and 20 minutes after the massage. Size of masseter muscle is measured by the ultrasonograph before and just after massage.

The temperature of facial skin is shown in Fig. 12 and the size of masseter is shown in Fig. 13. As a result of the massage of WAO-1, the temperature increases immediately after the massage, and keeps rising until ten minutes later. The amount of an increase after ten minutes was 0.8[C°].

Increase rate of the size of masseter muscle has increased 16.8%. As a result of the massage of doctor, increase rate of the masseter muscle size has increased 18.7%. In both cases, an increase was found. However, there was so no difference on the increase rate.

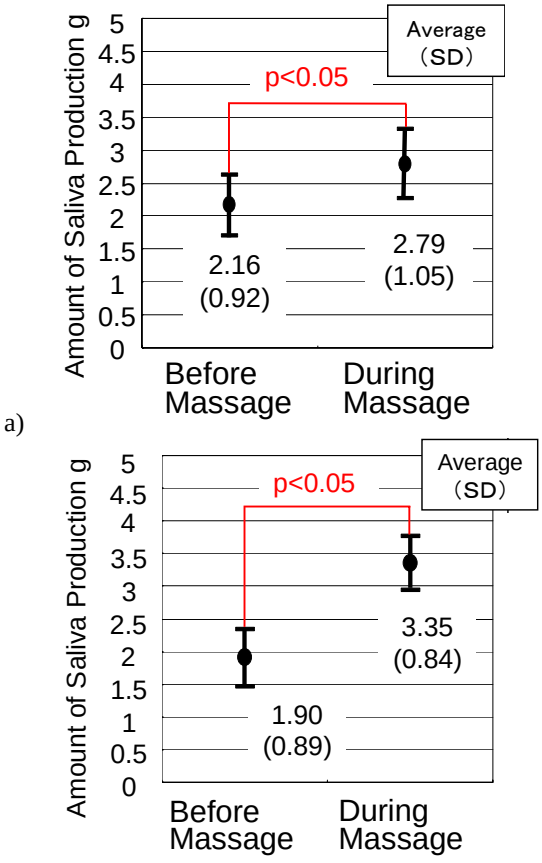


Fig. 11 Experimental results obtained by calculating the average of the production of saliva to subjects before and after providing the massage therapy by: a) WAO-1; and b) Doctor

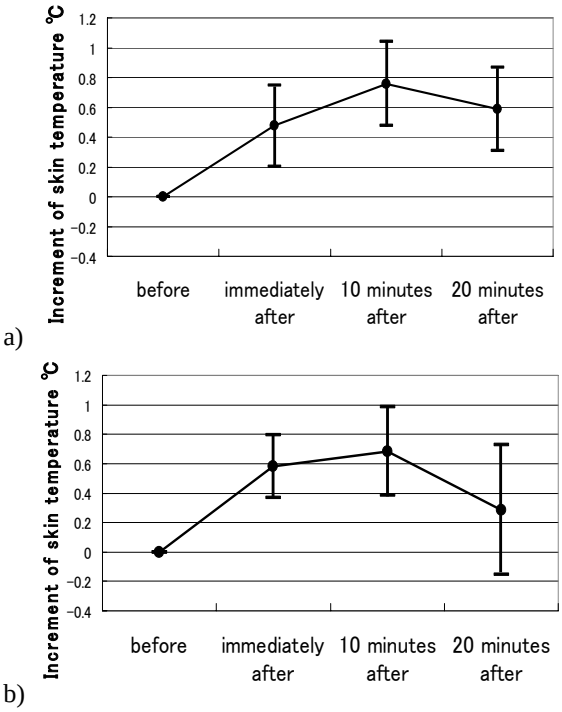


Fig. 12 Experimental results obtained by measuring the average of skin temperature from subjects before and after providing the massage therapy by: a) WAO-1; and b) Doctor

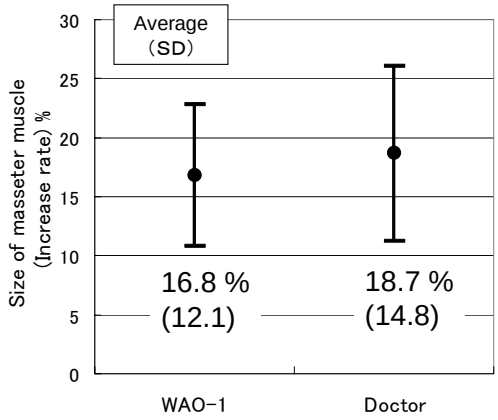


Fig. 13 Experimental results obtained by measuring the size of masseter muscle from subjects before and after providing the massage therapy by WAO-1 and a doctor

VI. Conclusion

In this paper, we presented the development of an oral-rehabilitation robot WAO-1 designed to provide massage therapy on the maxillofacial tissues in patients with oral health problems. In order to provide massage, two modules were considered to implement the control system: Massage pattern generator (offline) and a Virtual Compliance Control (online). The massage pattern generator was implemented used to define the massage trajectory from a CT image. The virtual compliance control was used to assure the stability of the system while providing the massage.

A set of experiments were proposed to confirm the effectiveness of the proposed of WAO-1. As a result of this experiment, we confirmed the increase of the production of saliva, size of masseter muscle and skin temperature. However, we require performing more detailed experiments to determine the real effectiveness of proposed robotic system while providing massage therapy.

Therefore, as future work, clinical tests with WAO-1 should be conducted in hospitals to confirm the effectiveness of its massage to the patient of dry mouth. As improvement of WAO-1, development of other kinds of plungers that have an optimal shape and consist of an optimal material is required. Furthermore, an automatic trajectory generation algorithm will be implemented.

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