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Development of the Airway Management Training System WKA-3 : Integration of Evaluation Module to Provide Assessment of Clinical Competence and Feedback Module to Reproduce Different Cases of Airway Difficulties

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Abstract—**An active training system is characterized by providing quantitative information of the trainee's performance of the task to the trainee, simulating real-world conditions of the task, and assuring training effectiveness. For this purpose, the authors have been developing an Airway management training system. In particular, we have previously presented an evaluation model system to acquire quantitative information for the trainee's performance, and an actuated model system for real-world conditions of the task. In order to fulfill all of the characteristics of the active training system; in this paper, we would like to propose an integrated system, Waseda Kyotokagaku Airway No.3 (WKA-3) which integrates the function of both system models. For this reason, we have focused on embedding sensors and actuators with the link drive mechanism and the wire drive mechanism to a conventional patient model towards the development of a patient robot. In this paper, we present WKA-3 how to design the mechanism and how to redesign several organs to embed the sensors for the measurement of the trainee's performance. A set of experiment have been carried out to doctor subjects using the WKA-3 to verify the effectiveness of the proposed system by asking doctors to evaluate the proposed system.**

I. Introduction

The evolution of advanced computerized techniques, computer assisted surgery, sensors, vision systems, etc., are revolutionizing the way doctors plan, perform, and follow-up invasive surgical procedures. In addition, the introduction of Robot Technology (RT) has enabled doctors to perform minimally-invasive surgery difficult to conceive by means of conventional techniques. Up to now, researchers and engineers have been particularly focused on developing novel surgical tools and training models. There is, in fact, a significant amount of surgical training currently performed on actual patients that can be compromising to both the patients and the hospitals. For that purpose, engineers have been introducing novel approaches to the training of medical students that may potentially reduce possible risks to the patients [1]. In [2], the concept of active training systems based on RT technology has been introduced as an approach to introduce more effective training systems. In particular, an active training system must fulfill at least three conditions: reproduce the real-world condition of the task, provide objective assessments of the training progress, and provide useful feedback to trainees [2]. Even though different kinds of active training systems have been proposed, most of them are designed to attach sensors to the medical instrument, which may affect the performance of trainees due to collisions between the tool and the patient model; as well as limit the surgical tool freedom of motion ([3-5], etc). Furthermore; trainees may have difficulties while performing the same task with real surgical tools because they are trained with a modified tool (different weight, dimensions, attachments, etc.).

For that purpose, we have proposed at Waseda University the development of a patient robot as a long-term project since April 2004. The design concept of the patient robot is based on two principles: to serve as an active training device and as an advanced evaluation tool for surgical instruments and medical procedures. In order to fulfill the three basic principles of an effective training system, the Patient Robot should: be designed to emulate the human body (both anatomically and physiologically), have embedded sensors into the simulator (not in the instrument), and have embedded actuators to provide feedback. Due to the complexity involved in the development of the Patient Robot, as an initial approach, we proposed the development of an Airway Management Training System [6]. In this paper, we are presenting the details of the Airway Management Training System.

Airway management is a basic skill that it is provided during emergency situations such as: cardiopulmonary arrest, multiple injury, etc. In general, airway management is not only provided in order to supply oxygen into the lung but also

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to protect the lung from gastric foreign bodies and bleeding due to an external wound. Even though it is a basic medical operation, different kinds of complications may arise due to unskilled operation. Furthermore, patients may present various kinds of airway difficulties and individual differences that may complicate the operation of airway management by clinicians not skilled enough in the task. As a result, technicians and students are required to practice airway management for several years in order to achieve proficiency.

For this purpose, we proposed a novel airway management training system in order to fulfill the effective training system. In [8], we presented the Waseda Kyotokagaku Airway No. 1 Refined (WKA-1R) which embeds sensor systems in order to provide quantitative information of a trainees' performance. The WKA-1R is composed of different kinds of embedded sensors such as: Force Detection Sensor system (FDSS), Position Detection Sensor System (PDSS), and Displacement Detection Sensor System (DDSS). The collected data is then integrated into an evaluation function that provides a quantitative assessment of trainees' skill. From the experimental results, the WKA-1R was able to quantitatively detect the differences among different levels of expertise (i.e. unskilled, medical students and anesthetists), and we also developed the Waseda Kyotokagaku Airway No.2 (WKA-2) in order to reproduce airway difficulties: various cases, individual difficulties in order to simulate real-world condition of the task. For the purpose of these, the WKA-2 has wire driven mechanism embedding 16 actuators and 16 Tension/Compression Detection Sensor System (TCDSS) in order to reproduce the airway difficulties [9-10].

As we have previously mentioned, the airway management training system should satisfy the three conditions of the active training system. For this reason, we propose Waseda Kyotokagaku Airway No.3 (WKA-3) which enables us to not only provide quantitative information of the training progress of the proposed task, but also to reproduce airway difficulties such as various cases, and changing the stiffness of the robot patient's muscles (Figure 1). The WKA-3 has not only integrated the function of WKA-1R and WKA-2, but has also greatly improved the performance of the sensor system, and the mechanism of the system relative to the previous system WKA-1R and WKA-2.

Regarding the force sensor for the measurement of the trainee's performance, the FDSS of WKA-1R has many problems: first the sensor can only measure compressive force, second the measurable range of force is limited, third it is required to deform the spring in order to acquire the voltage change, and lastly, friction always exists between the spring guide and the white reflective plastic, and calibration and maintenance for practicality.

Regarding the mechanism of the WKA-2, there are different problems to solve: Maintenance problem and low stiffness of mechanism due to using wire driving mechanism, low driving efficiency due to the friction between the wire tube and the wire, no precise position control due to uneven tension and the antagonized wire mechanism, and many actuators are used over than DOF of the motion of the human mandible and the tongue. In addition, the head, neck, and tongue can not move independently because the six wires attached on the mandible and the ten wires attached on the tongue are dependent mutually. This is the reason why it was difficult to apply the force control in the WKA-2.

In order to improve the performance of the force sensor, we developed Tension/Compression Detection Sensor System (TCDSS) which not only reinforces calibration and maintenance for practicality, but also enables us to measure tension, compression, and torque. In addition, all of the problems of the force sensor of the WKA-1R and the WKA-2 have been solved. Therefore, in the WKA-3, we adopted TCDSS as force sensor for the measurement of the trainee's performance, and force control [8].

In this paper, we will present the hardware of WKA-3 in detail how to design it, how to redesign several organs in order to embed the sensor for the measurement of the trainee's performance and also present the force control and position control of the WKA-3 in order to reproduce airway difficulties, the stiffness of the patient's muscles. Finally, doctor subjects have carried out a set of the experiments in order to verify the effectiveness of the WKA-3. The doctor subjects evaluate our system, give us their variable opinions, and we discuss the result of the experiments.

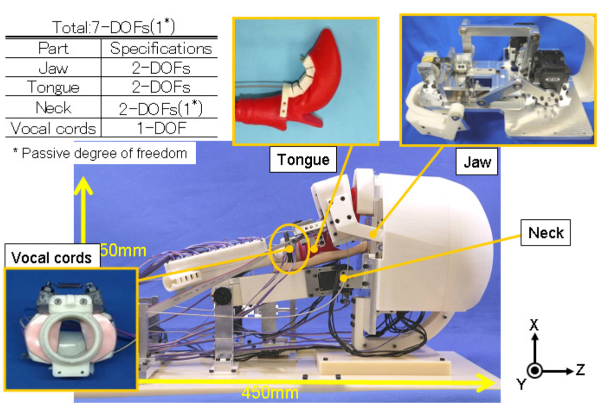

Fig.1 Waseda KyotoKagaku Airway No.3 (WKA-3)

II. WASEDA-KYOTOKAGAKU AIRWAY NO. 3

A. Design Concept

The procedure of the airway management can be described as follows: setting the optimum position and mouth opening, inserting a medical device (laryngoscope) into the oral cavity, lifting up the tongue with the laryngoscope to observe the vocal cords, inserting another medical device (endotracheal tube) between the vocal cords, positioning the endotracheal tube into the trachea, and finally inflating the endotracheal tube's cuff on the trachea to prevent foreign bodies from entering the lung. In order to measure quantitative information of the trainee's airway management performance, simulate the real-world conditions of the task, and assure training effectiveness, we are proposing the WKA-3, which integrates the functions of the WKA-1R and WKA-2.

As a result of these facts, the design concept of the WKA-3 should be considered as follows. The WKA-3 should reproduce the motion and various cases of the patients anatomically during the administration of airway

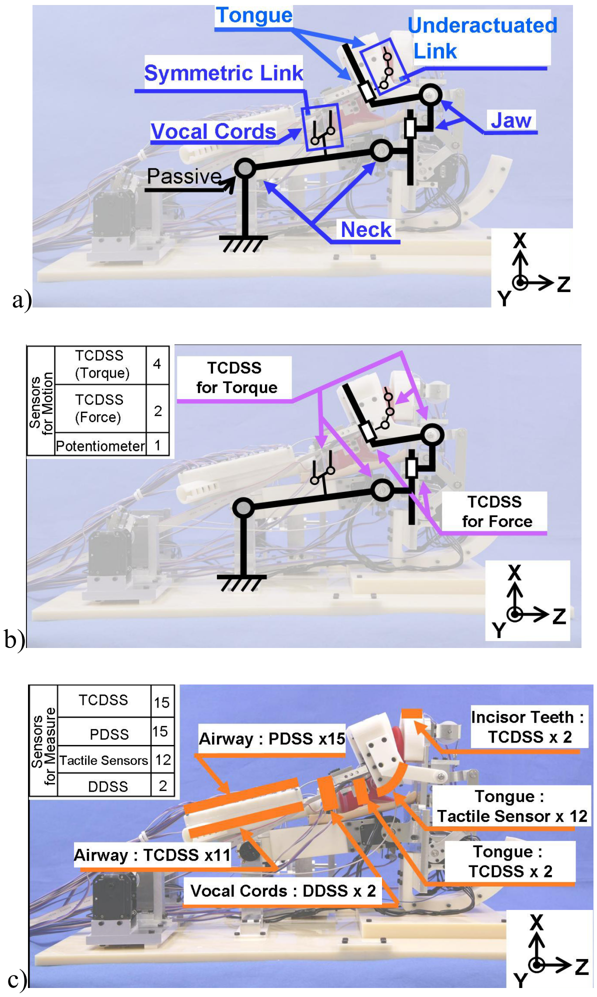

Fig.2 Specifications of WKA-3: a) Specification of the Parts; b) Specification of the Sensor for the Force Control; c) Specification of the Sensor for the Measurement of the Trainee's Performance

management, and all of the sensors for measuring the trainee's performance, and for force control, should be embedded in the WKA-3.

B. Configuration of Hardware

WKA-3 is composed of seven parts such as head, mandible, tongue, vocal cord, trachea, incisor teeth, and neck (figure 2.a). The WKA-3 has seven degrees of freedom (six active and one passive). The WKA-3 consists of the link drive mechanism and wire drive mechanism with six actuators for the motion of neck, mandible, tongue, and vocal cord. In particular, we propose the link drive mechanism for the mandible of the WKA-3 which simplifies the motion of the human mandible, and can reproduce airway difficulties such as restricted opening mouth, and mandible dental protrusion. We also propose wire drive mechanism for the motion of the tongue such as tongue swallowing and changing shape of the tongue, and the motion of opening and closing the vocal cord as shown in Fig. 2a. For the force control, we embed the TCDSS into each of the joints such as mandible, tongue, vocal and cord as shown in Fig. 2b. Moreover, in order to acquire the quantitative information of operator's performance of the task, we also embedded the TCDSS in the redesigned organs such as the incisor teeth, vocal cord, and trachea (figure 2c). Compared with the WKA-2, by simplifying the mechanism of the proposed system, we can only use six actuators.

The WKA-3 has the link drive mechanism and the wire drive mechanism. For the force control, an amount of the external force should be measured by embedding the TCDSS. For the purpose of this, we propose a *Translational Unit* and a *Rotational Unit*. The *Translational Unit* enables to measure the translational force along the linear guide by embedding the TCDSS and the *Rotational Unit* enables to measure the torque along the rotational axis. In order to transmit efficiently an amount of the torque to the wire, we also propose a *Wire Drive Unit* which consists of a *Rotational Axis Unit*, TCDSS for the torque, wire tube, and a pulley. The pulley and wire are fixed through the wire tube, and the pulley and the *Rotational Axis Unit* are assembled in order to measure the applied torque on the wire. Using these units, we can measure the applied force and the torque by the external force.

1) Mandible

During opening the mouth, with respect to the kinetic axis, human has 3-DOFs [9]. However, while performing the airway management, all of the motion of the mandible can be simplified in 2-DOFs. Therefore, we have implemented 2-DOFs which represent the rotational motion (θ) and translational one (L) as shown in Fig. 3a. In order to control the rotational motion and translational motion of the mandible, we have attached four link drive mechanism and crank drive mechanism to the actuators (Figure 3b). For the translational motion (L), the four links and the crank link are driven, and for the rotational motion (θ), the four links are driven (Figure 4). By calculating inverse kinematic model (Figure 5), we can also obtain an amount of the rotations (θ_{JawRot}, $\theta_{JawTrans}$) as shown in Eq.1-4. Compared with the WKA-2, using the four link mechanism and the crank link mechanism, we can decrease four actuators (the mandible of the WKA-2 is driven by six actuators). From the proposed mechanisms, the mandible of the WKA-3 can reproduce the range of the motion of the human's mandible as shown in Fig. 3b. An amount of the initial torque which applies all of weights including the mandible, the vocal cord, and the trachea are sustained on the each of the two actuators embedded on the mandible. By attaching a constant force spring, the weight will be canceled by the constant force spring. As a result of the fact, an amount of the initial torque which is exerted on the actuators attaching on the mandible can be decreased. Moreover, we attached the TCDSS for force and TCDSS for torque for the force control.

$$d_t = L1\sin\theta_{JawTrans} + \sqrt{L1^2\sin^2\theta_{JawTrans} - L1^2 + L2^2} \quad (1)$$

$$\theta_{JawTrans} = -\sin^{-1}((L2^2 - L1^2 - d_t^2)/(2\cdot L1\cdot d_t)) \quad (2)$$

$$g = \sqrt{d_r^{\,2} + L3^2 - 2d_r\cdot L3\cdot\cos\theta_{JawAxis}} \quad (3)$$

$$\theta_{JawRot} = 180 - \cos^{-1}\left[\frac{d_r - L3\cos\theta_{JawAxis}}{g}\right] - \cos^{-1}\left[\frac{L1^2 + g^2 - L2^2}{2 \cdot L1 \cdot g}\right] \quad (4)$$

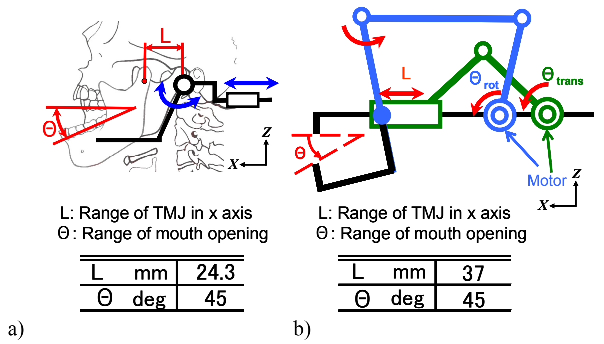

Fig.3 Range of mandible of human and WKA-3: a) Range of human mandible; b) Range of the mandible of the WKA-3

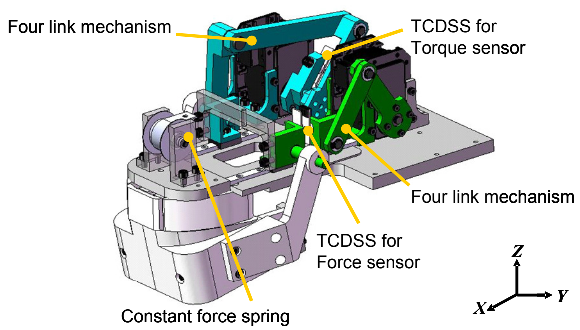

Fig.4 Mechanism of Mandible with link drive mechanism

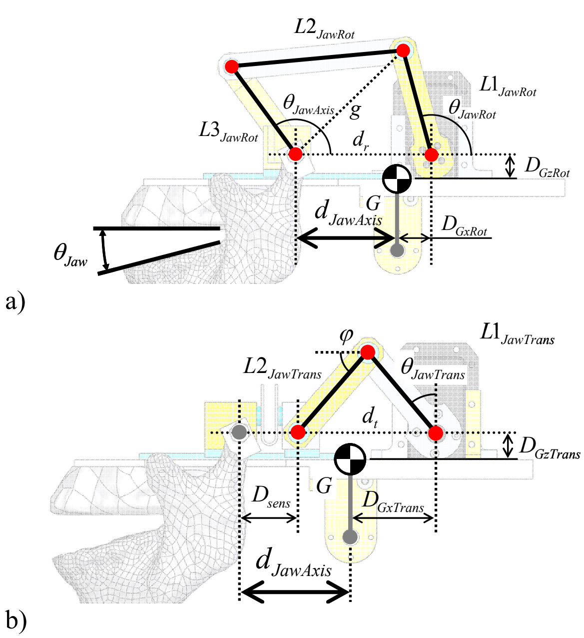

Fig.5 Kinematic model of the mandible of WKA-3: a) Kinematic model of four link drive mechanism; b) Kinematic model of crank link drive mechanism

2) Tongue

While operating airway management, we considered motion of the tongue. During airway management, according to the status of shape of the tongue, operators can have trouble in operating airway management. The shapes of the tongue block the airway, and disturb inserting the tube into the vocal cord. Therefore, for the development of the tongue, several things should be considered. When the patients have consciousness, the patients can breed by themselves, and at that time, the tongue always has an amount of the space *d* which is allowed to pass an amount of the air, (when patients have unconsciousness, all of muscles which are connected with tongue are relaxed) so tongue falls down to the pharynx and blocks airway which is called *tongue swallowing* [10]. At this time, in order to stably provide oxygen into the lung, the tube should be inserted into the vocal cord. Normally, the tongue obstruct operator from observing the vocal cord by the operator's eyes. Therefore, the operator lifts up the tongue by the medical device, laryngoscope, and insert the tube into the vocal cord. Even though the tongue has y-axis and z-axis motion, and various shapes, it can be simplified into x-axis motion and several shapes while airway management. For the purpose of these, we propose a linear guide mechanism, an under-actuated mechanism, and tensile spring for the tongue motions. The tongue mechanism has one translational with the linear guide mechanism and the other motion with under-actuated mechanism to change the shape of the tongue as shown in Figs. 6-7.

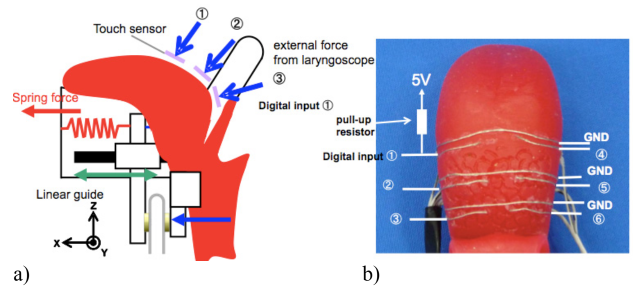

Fig.6 Specification of Tongue Mechanism: a) Tongue Mechanism b) Tactile Sensor on the Tongue

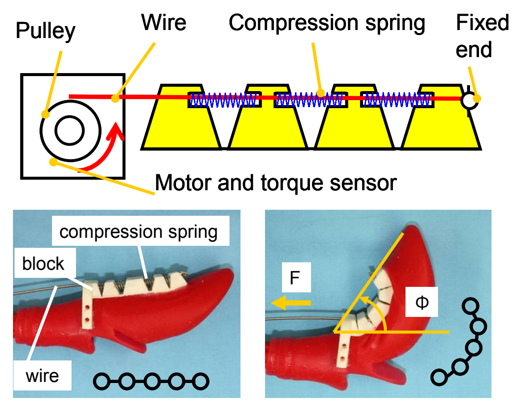

Fig.7 Motion of the Tongue Using the Under-actuated Mechanism

The tensile spring always pulls the wire and make it not to be slacked, and can apply position control along the x-axis. The under-actuated mechanism consists of blocks, wire, and compression spring. The array of blocks change the shape of tongue and compression spring can restore the original shape of the tongue when applying the tension by the wire as shown in Fig. 7. In addition, we also attached the tactile sensors on the tongue whether the medical device, laryngoscope is placed on the right side of the base of the tongue, and also attached TCDSS for the force on the base of tongue, and TCDSS for the torque on the *Wire Drive Unit* for the force control. Using these mechanisms, we can also decrease eight actuators.

4) Vocal cord

In order to reproduce laryngospasm which closes the vocal cord by the external stimuli to protect it from the foreign body and while putting patients under anesthesia, the vocal cord is always opened [11]. The WKA-1R has the vocal cord and measure the applied force, and the WKA-2 have the vocal cord, but cannot measure the applied force and cannot reproduce laryngospasm. Therefore, we propose the vocal of WKA-3 which can measure the applied force and reproduce laryngospasm. The vocal cord of WKA-3 consists of spring, rotational axis, elastic rubber ring, reflective elastic material, and wire (Figure 11). The actuator applies the force on the wire unit, pull the wire, and close the vocal cord. At this time, the spring here is a net restoring force on the mass, tending to bring it back to equilibrium. As a result of the fact, the vocal cord will be open. In addition, we also embed DDSS which consists of photo interrupter and elastic reflective material to detect the displacement applied by the endotracheal tube on the vocal cord.

5) Trachea and Incisor Teeth

In order to measure the position of endotracheal tube into the trachea, and measure pressure by the inflated cuff in the trachea, we designed the trachea. As stated in previous paper [6], we embedded array of the photo interrupters into the trachea, and also embedded the pressure sensor which consists of the array of TCDSS for the force sensor. In addition, In order to measure the applied force on the incisor teeth, we also propose incisor teeth embedding TCDSS for the force sensor. While operating tracheal intubation, unskilled performance traumatizes incisor teeth and breaks them.

6) Neck

In order to observe the vocal cord while operating the airway management, neck position also important factor in anatomy [12]. The neck of the WKA-2 was dependent of the wires attached on mandible and tongue. When the head is rotated by an amount of the angle, all of the wires attached on the mandible and the tongue should calculate the each of the lengths of the wires, but have the position errors (Absolute maximum error was 5.23 (mm). However, the neck mechanism of WKA-3 is independent of the tongue and the mandible. The motion of the neck will not affect the motion of the mandible, and the tongue as shown in Fig. 1. We also apply the force control by embedding the TCDSS for the torque with the *Rotational Axis Unit*.

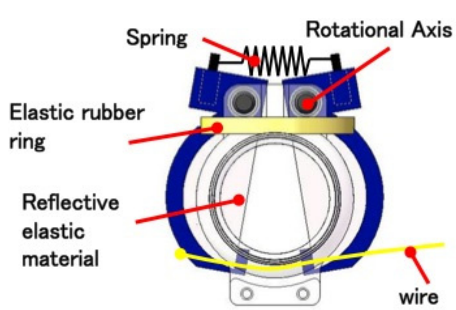

Fig.8 Vocal Cord of WKA-3

III. EXPERIMENTS & RESULT

Preliminary experiments have been carried out to reproduce the various cases of airway difficulties whether the various cases of the airway difficulties are satisfied with the human anatomy. For the purpose of this, we set the characteristic points of the various cases referring to the medical literature, and we compare the characteristic points with the various cases reproduced by the WKA-3. In the medical literature, for the patients who have unconsciousness, the tongue falls down to the pharynx, and for the patients who have consciousness, the tongue never falls down to the pharynx. From these facts, we can define the distance between the tongue and the pharynx. When the distance is 0 [mm], we can define it as the tongue swallowing. In case the distance is greater than 0, we can also state that it shows the individual difference of the patients and the degree of the consciousness. Using the WKA-3, we can reproduce the tongue swallowing, and we can also reproduce the normal tongue which has the distance form 0 [mm] to 20 [mm] (In MRI analysis, we found various normal tongue images which have the distance greater 0 [mm] less then 20 [mm])[13]. In the medical literature, Protrusion defines that the upper jaw protrudes from the mandible, retrusion defines that the mandible retrudes from the upper jaw [14]. Using the WKA-3, we can reproduce the protrusion which has distance from 0 to 22 [mm], and we can also reproduce the retrusion which has distance form 0 [mm] to -15 [mm]. By adjusting the various cases of the protrusion and the retrusion, we can also reproduce the individual difference of the patients. On the other hand, by applying Virtual Compliance Control [15], we can also reproduce the restricted cervical range and the restricted opening mouth. In the medical literature, the restricted opening mouth defines the distance between the incisor teeth of the upper jaw and the mandible is less than 30 - 40[mm] [16], and the distance of normal opening mouth is greater than 40 [mm]. By adjusting

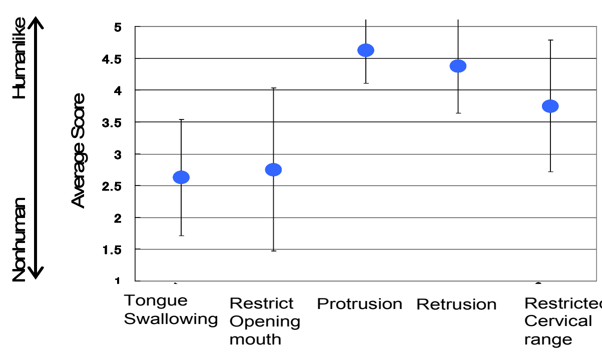

Fig. 9 Result of Questionnaire survey to the doctor subjects on the various case reproduced by WKA-3 (blue point is average, and error bar is standard deviation)

low virtual compliance coefficients such as spring and damper coefficient, we can also reproduce the normal opening mouth and by adjusting high virtual compliance coefficients the restricted opening mouth. In case of the restricted cervical range [17], by adjusting low virtual compliance coefficients, the WKA-3 can also reproduce normal cervical range, and by adjusting high virtual compliance coefficients the restricted cervical range.

From the preliminary experiments, we carried out a questionnaire survey of eight doctors whether the various cases reproduced by WKA-3 are similar with the various cases of the patients, and we also discussed the results of the questionnaire survey. The doctor subjects have experienced 4-13 years in the department of the anesthesiology. The procedures of the experiments are as follows. First, while we adjusted the one of the various cases reproduced by the WKA-3, each of the doctors performed airway management on the five cases such as tongue swallowing, restricted opening mouth, protrusion, retrusion, and restricted cervical range. Then, doctors checked their opinions on the questionnaire survey sheet. The doctors can evaluate their opinion in five levels (1 to 5) on each of the cases. Closer level 1 means non-humanlike reproduction by the WKA-3, and closer level 5 means humanlike reproduction by the WKA-3. In the experiments, the protrusion, and the retrusion reproduced by the WKA-3 are similar with the cases of the patients. Regarding the reproduction of the tongue swallowing, the doctors stated that it was not similar with the human, even though the WKA-3 reproduced various shapes of the tongue; they gave a lot of advice that the shape and the size of the tongue swallowing are different from the one of the human. Regarding restricted opening mouth and restricted cervical range, the doctors stated both of the two reproductions are not similar with the ones of the human..

IV. Conclusions & Future Work

In this paper, we have presented the details of the Waseda-KyotoKagaku Airway No. 3 (WKA-3), which embeds link-driving mechanism for the mandible, under-actuated and wire mechanism for the tongue, and wire mechanism for the vocal cords to mimic various cases of difficult airway using six actuators. Finally, a set of experiments was proposed to compare the various case produced by WKA-3 and the one produced by the human anatomy. In addition, we also verified the *Virtual Compliance Control* for each of the cases such as normal opening mouth, restricted opening mouth, and normal cervical range and restricted cervical range. Finally, we asked to eight doctors about the various cases reproduced by the WKA-3, discuss the result of the experiments, and they gave variable opinion to us.

As a future work, the doctors' variable opinion will be considered in future works, and we will also include evaluation of training effectiveness compared to the existing methods. (It is difficult, though, at least comparison to mannequins is indispensable.). In addition, we are proposing additional experiments using WKA-3. Trainees will perform airway management using WKA-3 in the various cases. We will obtain quantitative information on trainee's performance of the task, and verify the learning curve of the trainees.

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