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Development of Patient Scenario Generation which can Reproduce Characteristics of the Patient for Simulating Real-World Conditions of Task for Airway Management Training System WKA-3

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***Abstract*— Recently, in medical field, different training methods for medical staff have been proposed. However, the lack of knowledge on the real improvements of trainees makes difficult the real effectiveness of those proposed methods. Therefore, we are proposing an Active Training system for the effective medical training. The 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. In order to fulfill each of these characteristics, we have developed Waseda Kyotokagaku Airway No.3 (WKA-3) which makes it possible to obtain quantitative information for the trainee's performance and reproduce the various cases, individual differences for the airway difficulties for the simulating real-world conditions of the task. In this paper, we are proposing a *patient scenario generation* which can reproduce the characteristics of the patient simulating real-world conditions of the task for WKA-3. In emergent situation or surgical operation, the characteristics of patients are presented in the three parameters such as: *patient initial conditions*, *time variant status change*, and *reflex action*. By adjusting, and combining each of the three parameters, we can reproduce the various patient scenarios. In this paper, we also state how to generate the *Patient Scenario Generation* using the position control and virtual compliance control. Finally, a set of experiments has been carried out to the doctor subjects in order to verify effectiveness of the proposed *Patient Scenario Generation*, and discuss the doctors about the result of the experiments.**

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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 training of medical students that may potentially reduce possible risks to the patients [1]. In [2] and [3], the concept of active training systems based on RT 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. 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 ([4-6]). 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.), and such active training systems can simulate partially real-world condition of the task (reproduce feeling of being at real operation).

For this purpose; since April 2004, we have proposed at Waseda University the development of a patient robot as a long-term project. 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 Patient Robot, as initial approaches, we proposed the development of a Suture/Ligature Training System [7] and an Airway Management Training System [8-10].

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 situation 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 to prevent the lung from gastric foreign body 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 different kinds of difficult airway 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 WKA-1R enables to obtain the quantitative information of the trainees' performance of the task, and WKA-2 can simulate the real-world condition of the task. However, our training system should fulfill three conditions of the active training system, which reproduce the real-world condition of the task, provide objective assessments of the training progress, and provide useful feedback to trainees. For the purpose of these, we are proposing Waseda Kyotokagaku Airway No.3 (WKA-3) which can satisfy three conditions of the active training system (Figure 1). The WKA-3 has not only integrated the function of WKA-1R and WKA-2, but also improved the performance of the sensor system, and mechanism of the system compared to the previous systems (WKA-1R and WKA-2).

The previous version WKA-2 could reproduce the real-world condition of the task such as reproduction of the various cases [9]. These focuses on the time invariant characteristics of the patients, and these cannot satisfy the reproduction of the real-world condition of the task completely. In emergent situation or surgical operation, the patients are not stationary, and dynamically change their characteristics according to medical treatments or trainees' performance (dynamic or time variant characteristics of the patients) [11-13]. As a result of these facts, not only the static

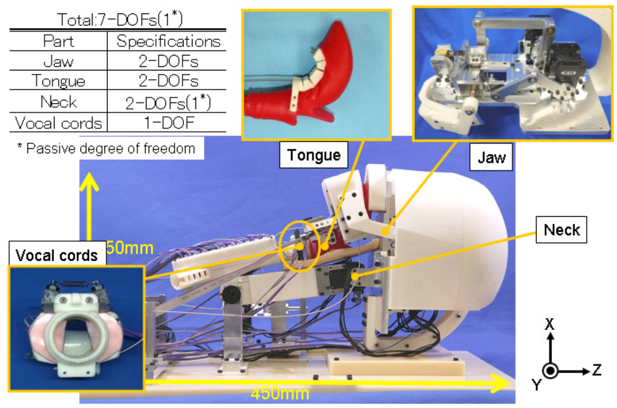

Fig.1 Waseda KyotoKagaku Airway No.3 (WKA-3)

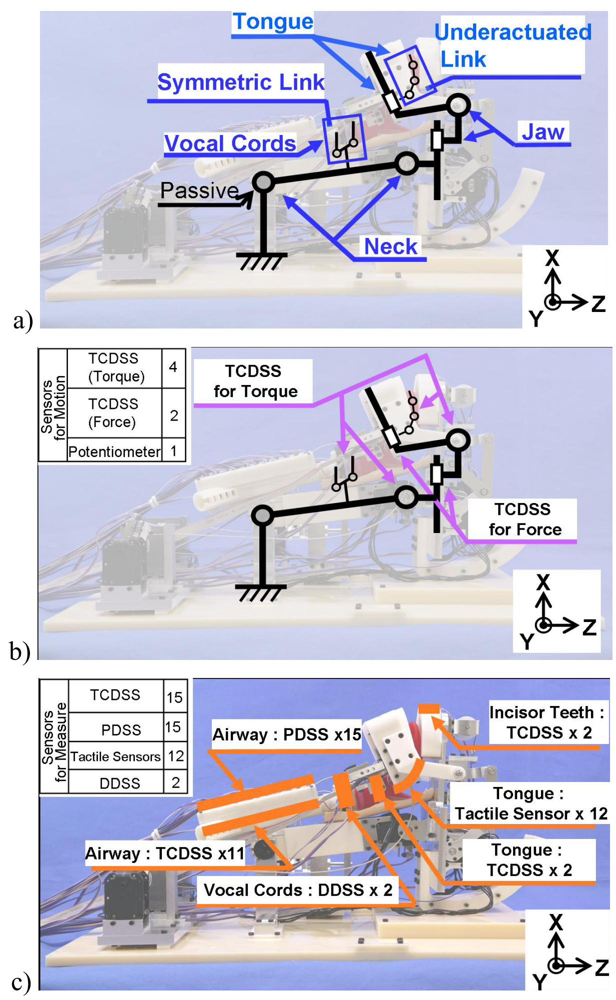

Fig.2 Specification of WKA-3: a) Specification of the Parts; b) Specification of the Sensor for the Force Control; c) Specification of the Sensor for the Measurement of the Trainee's Performance.

or time invariant but also the dynamic or time variant characteristics of the patients should be considered in reproducing real-world condition of the task.

In this paper, at first, we present the hardware of WKA-3 simply, and the *Patient Scenario Generation* which enables to reproduce both the time variant and invariant characteristics of patients. Particularly, we will present the characteristics of the patient, present how to design the *Patient Scenario Generation*, and present how to integrate it into WKA-3. Finally, in order to verify the effectiveness of the proposed *Patient Scenario Generation*, a set of experiments has been carried out to the doctor subjects.

II. WASEDA-KYOTOKAGAKU AIRWAY NO. 3

A. Design concept of WKA-3

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

As a result of these facts, the design concept of the WKA-3 should be considered as follows. WKA-3 can reproduce the motion and various cases of the patients anatomically while performing the airway management and all of the sensors for the measurement of the trainee's performance, and for the force control should be embedded in the WKA-3.

B. Configuration of Hardware

The WKA-3 is composed of seven parts such as head, mandible, tongue, vocal cord, trachea, incisor teeth, and neck. The WKA-3 has seven degrees of freedom (six active and one passive) as shown in Fig. 2a. In order to drive the mandible, neck, tongue, and vocal cord, the WKA-3 adopts the link drive mechanism and wire drive mechanism with six actuators. In particular, we propose the link drive mechanism for the motion of the mandible which simplifies the motion of the human mandible into 2-DOF, and can reproduce airway difficulties such as restricted opening mouth, and mandible dental protrusion as shown in Fig. 1. 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. 1. For the force control, we embed the TCDSS [10] 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, DDSS, PDSS, and Tactile Sensors in the redesigned organs such as the incisor teeth, the vocal cord, and the trachea (Fig. 2c).

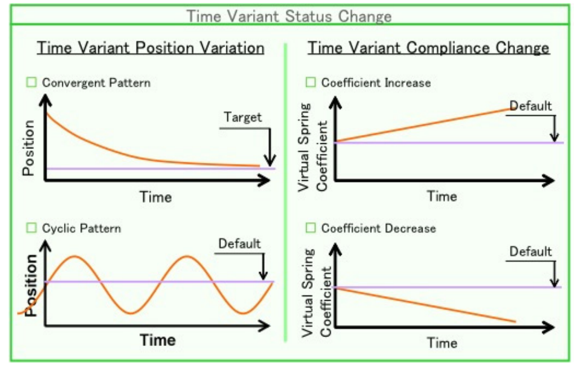

Fig.3 Time Variant Status Change

III. PATIENT SCENARIO GENERATION ALGORITHM

Our final goal of this research is to develop *Patient Scenario Generation*. As one of the *Patient Scenario Generation*, in this paper, we are focusing on the Airway Management Scenario Generation. As we stated in introduction, the patient has time invariant (static) characteristics, and time variant (dynamic) characteristics. While performing airway management in surgical operation or emergent situation, the patients have different characteristics. In case of the time invariant characteristics of the patient, we can define *patient initial conditions* as the parameters that the patients do not change their characteristics over time such as various cases including dental protrusion, restricted opening mouth, restricted cervical range, and tongue swallowing, and individual differences including the shape of tongue.

In case of the time variant characteristics of the patients, we can also define *Time Variant Status Change* as the parameter that the patients change their characteristics over time. The *Time Variant Status Change* has two parameters. One is *Time Variant Position Variation* which means the change of the patients' motions such as changing respiratory condition, changing the position of the mandible and tongue. For example, the motion such as breathing is periodic or slowly decreasing or increasing as shown in Fig. 3. The other one is *Time Variant Compliance Change* which means the change of the patients' conditions over time.

Furthermore, we can also define *reflex action* as the parameter that the patients enable to respond to the operators' performance or the external stimuli. As an example of the *reflex action*, laryngospasm (by the external stimuli, the vocal cord would be closed in order to prevent foreign body from the lung) and the cough are exampled [14]. By adjusting and combining these three parameters of the time variant and time invariant characteristics, we can reproduce various airway management scenarios.

IV. IMPLEMENTATION OF SCENARIO GENERATION ALGORITHM

As defined the characteristics of the patients as the three parameters for airway management scenario generation, in this section, we are considering how to implement airway management scenario generation using the proposed WKA-3. Particularly, we will describe in detail how to reproduce the

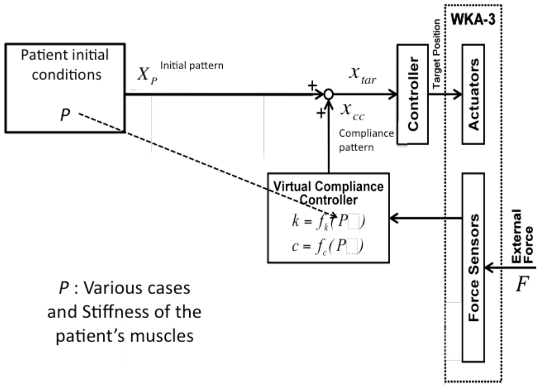

Fig.4 Airway Management Scenario Generation Algorithm with Time Invariant Characteristics of Patients

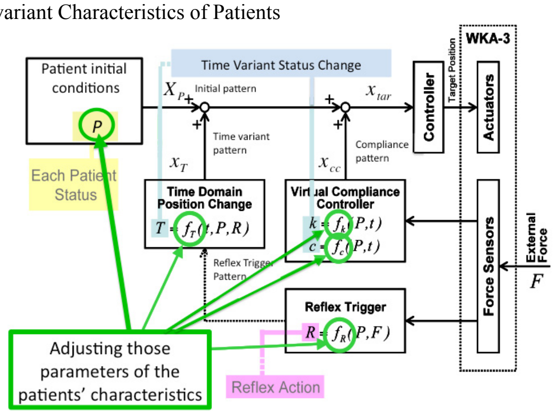

Fig.5 Airway Management Scenario Generation Algorithm with Time Variant Characteristics of Patients

airway management scenario generation by applying position and virtual compliance control into the WKA-3.

A. Position and Virtual Compliance Control

Humans have muscles on all of their bones, and when people move their arms, legs and neck, all of the muscles which are connected to the bones are contracted or relaxed. In order to reproduce human-like muscles, we consider applying force control into the WKA-3 which is called the *Virtual Compliance Control*. Generally speaking, the *Virtual Compliance Control* can simulate the stiffness of the end-effector by adjusting the *Virtual Compliance Coefficient* and *Virtual Damper Coefficient*. In our case, we applied the *Virtual Compliance Control* on each of the joints such as the neck, mandible, and tongue [15].

B. Airway Management Scenario Generation Algorithm with Time Invariant Characteristics of Patients

Scenario generation algorithm with time invariant characteristics of the patients is described as Fig. 4. As we stated in the Section III, the patient initial conditions *P* are defined as the parameters that the patients do not change their time invariant (static) characteristics over time such as various cases including dental protrusion, restricted opening mouth, restricted cervical range, and tongue swallowing, and individual differences including the shape of the tongue.

By adjusting the parameters of the patient initial conditions *P* such as the positions of the each of the actuators on the various cases, and virtual compliance coefficients, we can implement the *Airway Management Scenario Generation Algorithm* with the time invariant characteristics of the patients into the WKA-3 as shown in Fig. 4. We also specified the control block diagram how to implement the *Airway Management Scenario Generation Algorithm* for the WKA-3.

First, we adjust the initial pattern of the patient initial conditions *P* by combining the motion of each of the involved parts (such as mandible, tongue, neck and the vocal cord) and then such initial pattern is inputted into each of the actuators of the WKA-3. When an amount of the external force is applied from an external force $F_{ext}(t)$; the amount $x_{cc}(t)$ of the virtual compliance is calculated by adjusting the *Virtual Compliance Coefficient* and *Virtual Damper Coefficient* (Equation 1-4). The amount of the virtual compliance (compliance pattern) is compensated with the initial pattern of the patient initial conditions *P*, and the compensated pattern is inputted into each of the actuators of the WKA-3. Consequently, we can reproduce the *Airway Management Scenario Generation Algorithm* with the time invariant characteristics of the patients.

$$F_{ext}(t) = Kx_{cc}(t) + C\dot{x}_{cc}(t) \quad (1)$$

$$\dot{x}_{cc} = \frac{x_{cc}(t) - x_{cc}(t-\Delta t)}{\Delta t} \quad (2)$$

$$x_{cc}(t) = \left(K + \frac{C}{\Delta T}\right)^{-1} \left\{F_{ext}(t) + \frac{C}{\Delta t} x_{cc}(t-\Delta t)\right\} \quad (3)$$

$$x_{tar}(t) = x_{cc}(t) + X_P \quad (4)$$

$x_{cc}(t)$: Amount of virtual compliance (Compliance Pattern)
$x_{tar}(t)$: Target position
$F_{ext}(t)$: External force from Force Sensor (TCDSS)
$X_P(t)$: Initial pattern of the patient initial conditions
K : Time invariant virtual spring coefficient
C : Time invariant virtual damper coefficient

C. Airway Management Scenario Generation Algorithm with Time Invariant and Time Variant Characteristics of patients

As stated in the Section III, the parameters of the time invariant characteristics of the patients consist of *Time Variant Position Change* and *Reflex Trigger*. Particularly, the *Time Variant Position Change* has two parameters such as *Time Variant Position Variation* and *Time Variant Compliance Change*.

As stated in the *Airway Management Scenario Generation Algorithm* with the time invariant characteristics of the patients, we are adjusting the initial pattern X_P from the patient initial conditions *P*. The initial pattern also will be an input value of the *Time Variant Position Variation*, the *Time Variant Compliance Change*, and the *Reflex Action* as shown in Fig. 5. From the external force of the mandible, the neck, and tongue, the amount $x_{cc}(t)$ of the virtual compliance (Compliance Pattern) is calculated by adjusting the time variant *Virtual Spring Coefficient* $K(t)$ and the time variant *Virtual Damper Coefficient* $C(t)$ (over time, we can increase or decrease the *Virtual Compliance Coefficient* as shown in Fig. 3 and Eq. 5-8.

From the external force $F_{ext}(t)$, when the amount of the force is greater than the threshold value, the patients responses to the external stimuli. At this time, the time variant parameters *R* (Reflex Trigger Pattern) of the *Reflex Trigger* can be obtained. The Reflex Trigger Pattern *R* will be an input value of the *Time Invariant Position Change*. Finally, the time variant pattern of the *Time Variant Position Change* and the compliance pattern of *Time Variant Compliance Change* are compensated with the initial pattern into the WKA-3, and the compensated pattern is inputted into each of the actuators of the WKA-3. Consequently, by adjusting the various time invariant parameters and time invariant parameters, we can produce the various airway management scenarios.

$$F_{ext}(t) = K(t)x_{cc}(t) + C(t)\dot{x}_{cc}(t) \tag{5}$$

$$\dot{x}_{cc} = \frac{x_{cc}(t) - x_{cc}(t-\Delta t)}{\Delta t} \tag{6}$$

$$x_{cc}(t) = \left(K(t) + \frac{C(t)}{\Delta T}\right)^{-1} \left\{F_{ext}(t) + \frac{C(t)}{\Delta t} x_{cc}(t-\Delta t)\right\} \tag{7}$$

$$x_{tar}(t) = x_{cc}(t) + x_T(t) + X_P \tag{8}$$

$F_{ext}(t)$: External force from Force Sensor (TCDSS)
$K(t)$: Time variant virtual spring coefficient
$C(t)$: Time variant Virtual damper coefficient
$X_p(t)$: Initial pattern of the patient initial conditions
$x_T(t)$: Time variant pattern
$x_{cc}(t)$: Amount of virtual compliance (Compliance Pattern)
$x_{tar}(t)$: Target position

V. EXPERIMENTS & RESULT

Reproduction of Two Scenarios using WKA-3

Using this scenario generation algorithm, a set of the experiments has been carried out by 8 doctors in order to verify its effectiveness. Particularly, we reproduce two scenarios using WKA-3 the doctor subjects perform the airway management (tracheal intubation), and then we obtained doctors' variable opinions on the questionnaire about the two scenarios. The doctor subjects have 4-13 years experience in the department of anesthesiology. The first scenario involves patients with acute respiratory problem. In this case, muscles connecting neck and mandible are contracted. As a result of the fact, the patient cannot stay in a sniffing position (optimum position of the head and neck in order to observe the vocal cord). At this time, by injecting muscle relaxant into the patients, we make the patients' muscle relaxed for the sniffing position as shown in Fig 6a, and finally, we perform the tracheal intubation which is a procedure that operator inserts the tube into the vocal cord.

Second scenario is a general case of the patients. Due to the cardio pulmonary arrest or general anesthesia, the patients have a respiratory arrest completely. All of the muscles are relaxed, and tongue falls down to the pharynx which is called tongue swallowing. At this time, we should perform the airway management tracheal intubation) to provide oxygen into the lung as fast as possible as shown as in Fig 6b. Form the two scenarios generations, we obtained variable doctors' opinions on the questionnaire. The results of the questionnaires on the each of the experiments are as shown in the right side of the Figure 6.

A. Doctors' Opinion of the Two Scenarios on the Questionnaire

The eight doctors performed airway management on each of the two scenarios. Then, doctors checked their opinions on the questionnaire survey sheet. The doctors can evaluate two points such as *reality* and *reproducibility* in five levels (1 to 5) on each of the reproduced scenarios. The point of *reality* is how the reproduced scenario really happens many times in real situations such as the emergent situation and the surgical operation. At this time, closer level 1 means that it does not happens many times in real situations, but closer level 5 means that it does happens many times in real situations. The point of the *reproducibility* means how the reproduced scenarios are similar with the real patients. Closer level 1 means that it is not similar with the real patients, but closer level 5 means that it is similar with the real patients.

In case of the scenario one, we reproduce it for an emergent situation, but the doctor subjects are Anesthesiologists, and they are not emergent medical technicians. The doctor subjects state that it is a rare case that doctors operate airway management for the patients with Acute Respiratory Problem in surgical operation (that is why the reality was low score as shown in Fig. 6a). Muscle relaxant should be injected into the patients, and these procedures are mandatory. Regardless of

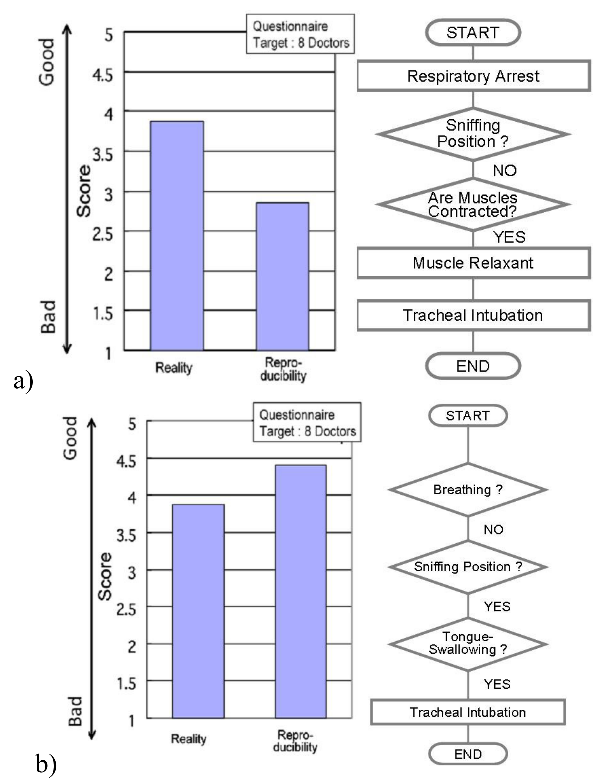

Fig.6 Experimental results: a) Example 1 of Scenario Generation ; b) Example 2 of Scenario Generation

the muscle rigidity, muscle relaxant should be injected into the patients. However, doctors' opinions are limited in the field of Anesthesiology. In the emergent situation, this also happens.

Muscle relaxant has various individual differences, some people are affected by the muscle relaxant very quickly, and others are not. Effects of the muscle relaxant are different according to the patients. This also depends on the kinds of the muscle relaxants. Some muscle relaxants have quick effects while others are slower. Therefore, the scenario is not connected to which muscle relaxants are used before reproducing the scenario. From these doctors' opinions, this is why reproducibility is low score as shown in Fig. 8. In case of scenario two, the doctor subjects gave high score on the questionnaire in the part of reality and reproducibility. This scenario could reproduce real situation, by injecting the general anesthesia or cardio pulmonary arrest resulting in a sudden respiratory arrest. At that time, we should perform the airway management. This is really natural scenario in the emergency situation and the surgical operation. At that time, all muscles are relaxed, and the tongue falls down to the pharynx (tongue swallowing). We could also reproduce the tongue swallowing.

The doctor subjects were surprised at the reproduction of the motion of the tongue, and mandible because the other patient simulators for the airway management cannot reproduce these functions. Even though commercial patient simulator also can reproduce the scenario, they focus on the circulatory system of the patient. They also found the merit of the WKA-3 because the actuators make the system to reproduce like real patients.

VI. 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. We also present the basic design for the patient scenario generation algorithm, and from the doctors' questionnaires, we obtained their different opinions. As a future work, we will reproduce various cases of the patients, and various scenarios using the WKA-3 in order to practice more effective medical training for the airway management. In addition, we will apply this scenario generation into not only airway management training, but also any other medical training. Finally, we are proposing additional experiments using WKA-3. Under the various patient scenarios, trainee will perform the airway management using WKA-3, and at that time, we will obtain the quantitative information of the trainee's performance on each of the patient scenarios, and verify the learning curve of the trainees.

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