ORIGINAL ARTICLE https://doi.org/10.4047/jkap.2023.61.4.257

치의학 교육을 위한 프로토타입 시뮬레이터의 개발

Development of a prototype simulator for dental education

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Purpose. The purpose of the study was to fabricate a prototype robotic simulator for dental education, to test whether it could simulate mandibular movements, and to assess the possibility of the simulator responding to stimuli during dental practice. **Materials and methods.** A virtual simulator model was developed based on segmentation of the hard tissues using cone-beam computed tomography (CBCT) data. The simulator frame was 3D printed using polylactic acid (PLA) material, and dentiforms and silicone face skin were also inserted. Servo actuators were used to control the movements of the simulator, and the simulator's response to dental stimuli was created by pressure and water level sensors. A water level test was performed to determine the specific threshold of the water level sensor. The mandibular movements and mandibular range of motion of the simulator were tested through computer simulation and the actual model. **Results.** The prototype robotic simulator consisted of an operational unit, an upper body with an electric device, a head with a temporomandibular joint (TMJ) and dentiforms. The TMJ of the simulator was capable of driving two degrees of freedom, implementing rotational and translational movements. In the water level test, the specific threshold of the water level sensor was 10.35 ml. The mandibular range of motion of the simulator was 50 mm in both computer simulation and the actual model. **Conclusion.** Although further advancements are still required to improve its efficiency and stability, the upper-body prototype simulator has the potential to be useful in dental practice education. (J Korean Acad Prosthodont 2023;61:257-67)

Keywords

Dental education; Mandibular movement; Robot patient; Simulator

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Article history Received July 10, 2023 / Last Revision July 20, 2023 / Accepted July 24, 2023

This work was supported by Seoul National University Research Grant in 2019.

Introduction

The clinical practice education provided to students is a core curriculum in the field of dental education. Although various teaching aids and materials have been used as auxiliary, some training courses are still conducted with actual patients.

However, dental education is currently facing a number of challenges, such as the reluctance of patients to receive treatment from inexperienced students,[1] the impact of COVID-19 on the learning curriculum,[2] and ethical concerns in medical practice.[3,4] Consequently, dental students lack many opportunities to provide dental treatment directly to patients, which can impede their access to the clinical exposure required to develop their practical skills.

Moreover, for dental training, dental students primarily rely on extracted teeth, dentiforms, or oral models placed on a phantom head that resembles the head and neck of the human body. However, dentiforms and phantom heads have a certain limitation because they do not respond at all as patients and are far from the actual treatment.[5]

Hence, to address these issues, the use of robot systems has been proposed in the dental education field. With the aid of haptic interface technology and advanced simulation, dental students can fulfill their basic learning needs through proper preclinical training prior to interacting with real patients in clinical settings.[6-9]

According to the study conducted by Tanzawa *et al*.,[10] it has been reported that the robot patients can reproduce comparable scenarios to those encountered with real patients. In this study, nearly half of the students gave a higher score to factors such as 'oral cavity', 'movement', and 'conversation' higher when accessing their responses to the robot patient. Moreover, 95% of the students preferred the robot patient over traditional mannequins, and 88% of the students thought it was essential to incorporate the robot patient into dental education. In addition, another study evaluated the student responses to medical emergencies in the dental setting, and the results showed that 78% of students recognized the efficacy of the robot patient in medical emergency training.[11]

In dental education, it is also important for dental students to understand the basic movements of the mandible in order to comprehend the functional anatomy of the human head. Maxillomandibular relationship is one of the most complex movement pattern in the human body, and the understanding of this can be challenging for students in their curriculum.[12,13] Furthermore, mandibular movement is important in the functional evaluation of the temporomandibular joint (TMJ).[14,15] For this reason, articulators are used to reproduce or simulate mandibular movements during clinical education or prosthetic treatment with maxillomandibular relationships.[16,17] However, it is difficult to simulate mandibular movement precisely as the jaw movement is composed of a complex combination of translational and rotational movements.[18]

Accordingly, it is crucial to create a robot patient that responds similarly to the patient, even though it is not identical to the actual patient, and that can simulate the mandibular movement pattern as well. It encourages a setting in which students may learn how to communicate with patients while also gaining dental knowledge and skills.

The purpose of the study was to fabricate an upper-body prototype simulator for dental education, to test whether it could simulate mandibular movements and to assess the possibility of the stimulator responding to stimuli during dental practice.

Materials and methods

Virtual simulator model generation

This study was approved by the Seoul National University Dental Hospital institutional review board (approval no. ERI23019). The cone-beam computed tomography (CBCT) data of a male subject aged 27 with normal anatomical structures was used for this study. A virtual simulator model was created by segmenting the hard tissues based on the CBCT DICOM data of the subject using 3D image analysis software (Mimics 19.0; Materialise NV, Leuven, Belgium) (Fig. 1). For the fabrication of a prototype simulator, the hard tissue segmentation of the head and neck region was performed. And then, the determination and registration of the skeletal structures as well as the mandibular position were performed based on the computer-aided design (CAD) files exported as stereolithography (STL) files. After that, the simulator was 3D printed using polylactic acid (PLA) material for the hard tissues. For the simulation of the soft tissues, a prefabricated silicone face model (Face Mannequin; Taekang Industry, Seoul, Korea) that fits the printed facial skeletal frame of the model was used. Dentiforms (TRM 406; Mtk, Guri, Korea) were also connected to the skeletal frame of the simulator model.

Developing internal systems

To simulate the primary movements of the mandible, servo actuators (XH430; ROBOTIS, Seoul, Korea) were used to generate the movements of the simulator. It was aimed at linking the structures in a way that mimics the TMJ of a human. A water sensor of 28 mm in width and length and 15 mm in depth (SEN0204; DFRobot, Shanghai, China) and six pressure sensors of 9 mm in diameter and 0.97 mm in depth (RA9; Marveldex, Seongnam, Korea) were attached inside the neck and the oral cavity, respectively, to control the response of the patient simulator to dental treatment. A display was also installed separately to design the simulator in accordance with its response to pressure during dental treatment.

Water level test

To measure water level, a pipette with overfill (Falcon® 10 ml Serological Pipet; Corning Life Sciences, Glendale, AZ, USA) and a pipette controller with a volume measurement range of 0.5 to 100 ml (Falcon® Pipet Controller; Corning Life Sciences, Glendale, AZ, USA) were used to inject water into the oral cavity of the robot patient until the sensor made an alarm. The same experiment was repeated 10 times, and the amount of injected water was recorded for each time. The average value of these 10 trials was regarded as the specific threshold of the water level sensor. During the experiment, the patient robot was in a supine position so that the water flowed through the oral cavity. A beaker (Duran® Beaker; Duran®, Mainz, Germany) was used to collect the water from the oral cavity of the simulator.

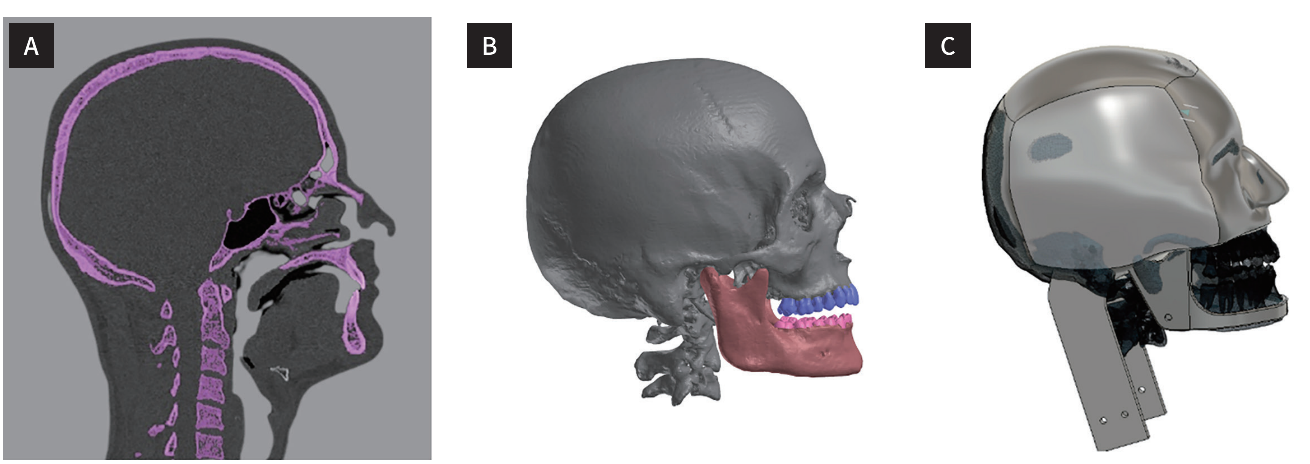

Fig. 1. Development of a virtual simulator model frame using CBCT. (A) Segmentation of hard tissues, (B) 3D skeletal model, (C) CAD design.

Simulation performance and reliability validation

To fabricate the prototype simulator, the virtual simulator model was used in computer simulation. The computer simulation of the mandibular movements of the simulator was performed in a 3D simulation program (fusion 360 motion study; Autodesk, San Rafael, CA, USA). In order to determine the simulator's mandibular range of motion and to compare with that of a human, its maximum mouth opening (MMO) was measured in the 3D measurement program (Geomagic Control X, version 2017.0.3; 3D systems, Rock Hill, SC, USA) by importing the STL file. For verification purposes, using a digital vernier caliper (CD-15CP; Mitutoyo, Kanagawa, Japan) the MMO was also directly measured in the actual simulator model.

Results

External configuration

The upper-body prototype simulator consisted of an operational unit, an upper body with an electric device, a head with a TMJ, and dentiforms (Fig. 2).

Internal configuration

Lead screws convert the rotational movement of servo actuators into translation. Furthermore, the servo actuator for the rotational joint of the mandible has a bevel gear that allows the actuator to be located remotely because the servo motor is too large to connect directly to the mandibular rotation joint.

Small sub-motors link actuators at each joint, and lead screws and bevel gears maintain the position of the TMJ. The TMJ of the simulator was capable of driving two degrees of freedom, implementing rotational and translational movements, which are the most important movements in the opening and closing of the mandible (Fig. 3).

System configuration

OpenCR as the microcontroller detects the input of each sensor and control switch. Moreover, based on the input, the target position command is applied to the actuator that drives each joint of the simulator, and the load (force) is received. The actuators control the position of each joint, measure positional and force information, and transmit it. The head of the simulator was equipped with an LED that displays the state and water level of the oral cavity. A buzzer was also used to convey the status of the simulator audibly.

The water level sensor can detect the water level in the oral cavity of the patient simulator, and if the sensor detects that the water level has risen due to poor suction during treatment, it will sound an alarm or display a vi-

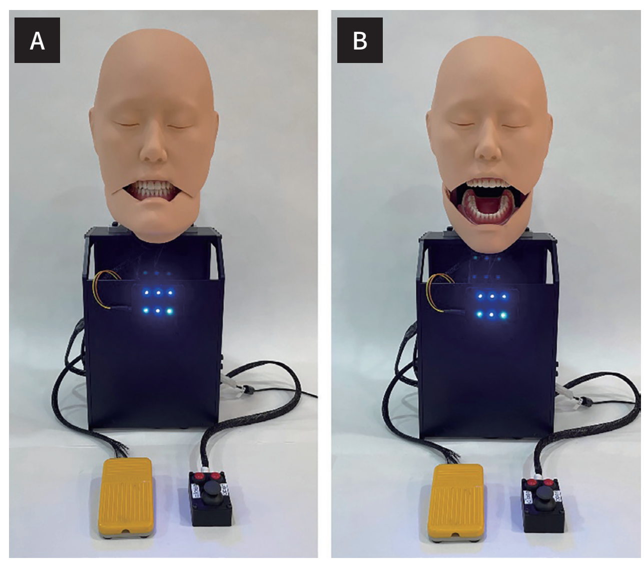

Fig. 2. The upper-body prototype simulator. (A) Jaw closing, (B) Jaw opening.

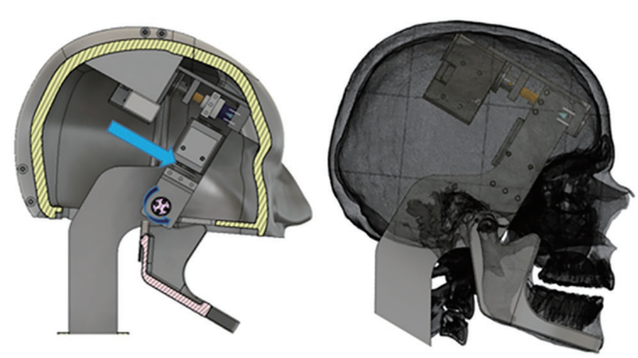

Fig. 3. Internal structures of a simulator head.

sual alert via an LED on the head. According to the water level test in this study, the specific threshold of the water level sensor was 10.35 ml on average. The water level at which the water sensor responded in each trial is shown in Table 1. Pressure sensors were attached to the inner surfaces of the silicone face model and the outer and inner surfaces of the dentiforms, which represent the human gingiva and the facial soft tissues, respectively. The responsive range of the pressure sensors was from 5 g to 4000 g. These sensors can detect the pressure applied by the operator during dental treatment, and the display separately installed in the simulator can respond to it. The display showed a green or blue color when light pressure was applied and a red color when excessive pressure was applied.

The control unit was configured to organize the simulator through three parts: control pendant, joystick, and foot switch. The control pendant, foot switch, and joystick that can perform opening and closing movements can finely adjust each joint, but this works only when the foot switch is stepped on to prevent malfunction (Fig. 4).

Simulation performance analysis

The 3D simulation performance analysis revealed that the upper-body prototype simulator had a mandibular range of motion of 50 mm and an opening movement of 28.6 degrees, as shown in Fig. 5 and Fig. 6. Additionally, the measurement of the MMO of the actual simulator

Table 1. Threshold values for water level test

Water level test	Specific threshold (ml)
Trial 1	10.8
Trial 2	9.9
Trial 3	10.7
Trial 4	10.4
Trial 5	10
Trial 6	10.7
Trial 7	10.2
Trial 8	10.4
Trial 9	10.5
Trial 10	9.9
Average	10.35

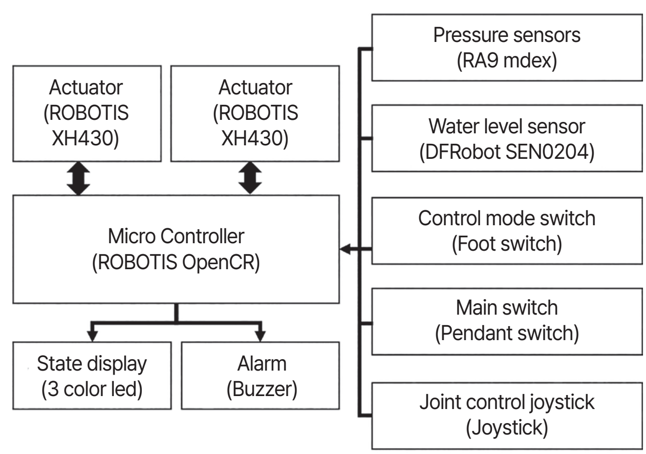

Fig. 4. System configuration chart.

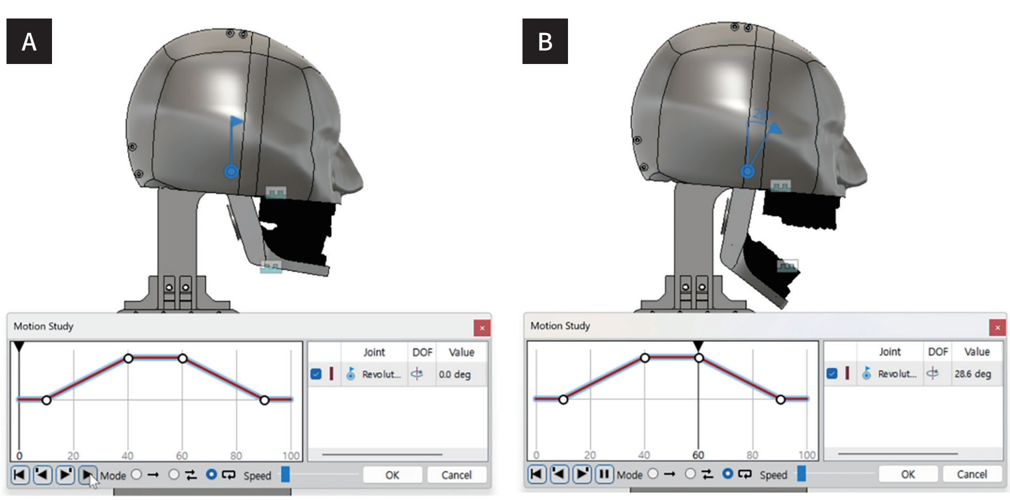

Fig. 5. The computer simulation of the mandibular motion of the simulator. (A) Jaw closing, (B) Jaw opening.

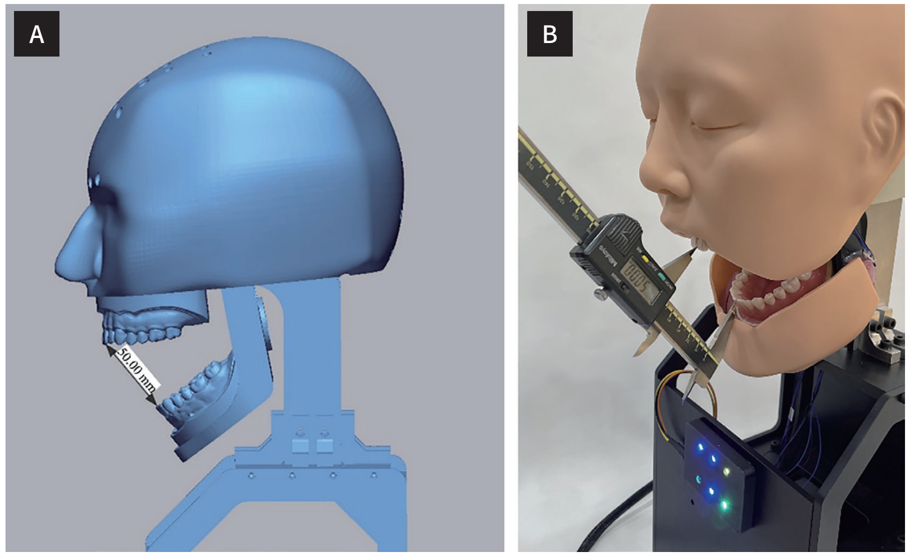

Fig. 6. Measurement of mandibular range of motion of the simulator. (A) In a 3D measurement program, (B) With a digital vernier caliper.

model was 50 mm, which is within the range of the MMO of an adult.

Discussion

Simulation-based dental education is an effective approach to dental professional development. It offers a safe and controlled dental practical environment for dental students without any potential harm to patients. One previous study assessed the improvement in attitudes of dental students regarding the use of a full-body patient simulation system (SIMROID) compared to the existing mannequin (CLINSIM) in the field of dental clinical education.[19] The authors verified the effectiveness of SIMROID in improving the attitudes of dental students towards patients, with a majority of students expressing that SIMROID was similar to real patients. Currently, various types of dental simulators have been introduced in the dental education field.[10,11,20-22]

This study endeavored to introduce an upper-body prototype simulator for dental education. Moreover, in the study, it was analyzed how the prototype simulator can simulate mandibular movement and the possibility of the simulator responding to stimuli during dental practice as well.

As external configurations, the upper-body prototype simulator used in this study comprised an operational unit, an upper body with an electric device, a head with a TMJ and dentiforms. Likewise, a study by Tanzawa *et al*. also developed a robotic patient simulator by reproducing oral and maxillofacial anatomical structures and functional movements for dental treatment.[10] However, a notable difference between the patient simulator in this study and that of other studies is that that the simulator in other studies allows dental students to interact with a control program for communication purposes. The authors reported that 53% of the students gave positive feedback about the "conversation" feature of the reproducibility of the patient simulator based on their responses to the questionnaire.

In the aspect of using sensors, the head of the patient simulator was equipped with an LED that displays the state and water level of the oral cavity, along with a buzzer that audibly conveys the status of the simulator. Previous studies have reported that if intra-oral fluids are not effectively suctioned during dental treatment, the remaining fluids can stimulate the cough reflex as a protective response to the respiratory tract.[23,24] Therefore, a small water level sensor was also attached to the neck of the simulator, and when the oral cavity of the patient simulator is filled with water due to improper suction, it will signal through an LED light visually or by a buzzer audibly. Additionally, the water level test in this study indicated a specific threshold level of the water level sensor was 10.35 ml. Likewise, in a study by Hanamoto *et al.*,[25] 10 ml of water was used to investigate the incidence of cough reflexes and the impact of head position and mouth opening on swallowing performance in the supine position. On the other hand, several studies have reported that high-speed handpieces or ultrasonic scalers can result in 30 to 50 ml of water injection into the oral cavity per minute.[26-30] This significant amount of water accumulation causes difficulties for patients in swallowing. Therefore, ensuring proper suction is important to effectively remove the intra-oral fluids and maintain patient comfort during treatment. With the inclusion of a water level sensor in the simulator, students can detect the discomfort of the patient simulator and subsequently avoid being careless. However, the current simulator lacks a drainage system, and further development is required to address the drainage issue.

Furthermore, during dental practice, dentists should handle oral tissues gently without applying excessive pressure. Therefore, in this study, pressure sensors were used to detect the amount of pressure applied by the operator. If excessive pressure was applied to the silicone face skin due to improper handling by the students, the display changed to a red color. In a quantitative sensory test conducted by Rolke *et al.*,[31] it was found that the average pressure-pain threshold for both cheeks (faces) was 212 kPa. One study introduced a medical emergency robot that aims to help dental students become familiar with emergency situations and learn how to deal with them.[21] Having the ability to evaluate and respond to pain or discomfort from a patient's expression or physical condition during dental treatment is crucial for dentists.[32] This skill can ensure that patients receive dental services in a safe and comfortable manner.[33]

Additionally, the current research also evaluated the ability of the simulator to replicate the human mandibular movements. Generally, the mechanism of mouth opening in humans involves complex combined movements of rotation in the lower TMJ compartment (condyle-articular disc) and of translation in the upper compartment (mandibular fossa-articular disc), which are concurrently performed in each stroke of mandibular movement.[34,35]

The TMJ of the patient simulator in this study was capable of implementing rotational and translational movements, which are the most important movements in the opening and closing of the mandible. In dentistry, articulators are used to replicate or imitate the mandibular movements during prosthetic procedures or clinical education.[16] However, this simulator, as compared to commonly-used semi-adjustable articulators, had similar rotational and translational movements, with differences in their respective degrees of freedom. Unlike the articulators, the human upper-body simulator had the advantage of directly reproducing the mandibular motion simulation comparable to that of a real patient and thus simulating the human body by reacting similarly using various sensors.

Concerning the reproducibility of the range of mandibular movement, the patient simulator in this study adhered to Posselt's mandibular range of motion,[36] where the average length of the sliding is 50 - 60 mm in the vertical direction.[37] In this study, the mandibular range of motion was 50 mm, consistent with the previously reported mean MMO ranging from 46.93 to 57.11 mm.[38] On the other hand, this study introduced a prototype simulator that was based only on the characteristics of adult males. According to many other studies, there are variations in anatomical and functional characteristics in relation to age, gender, and race,[39-41] and it can be suggested that it would be better to create various specific robotic patient simulators.

Furthermore, in this study, to determine the accuracy of the simulator fabricated with the CAD files, the predicted MMO value on the computer simulation and the MMO value measured in the actual simulator model were also compared. The result showed that there was no difference between these two, showing a value of 50 mm, respectively, and this could be verified as the reproducibility of the prototype simulator.

The technology of robots has been continuously developed over time, enabling them to carry out repetitive and dangerous tasks that are difficult for humans to perform. This is why robots are highly reliable, efficient, and consistent in their work,[42] and they can also reduce the need for human labor for more important tasks such as interacting with patients or other functions that require high cognitive skills.[43] This can also suggest that there is potential for robots to be developed as assistants for dental treatments.

However, since the utilization of hardware in dentistry is difficult and costly, there is still a lack of sufficient scientific evidence and limited acceptance for widespread practical application.[44] This is why research on dental robots in universities can serve as a potential propagator for the acceptance of robotic systems.[45] Given the various prospects for the integration of dentistry and robotics in the future, the development of a prototype simulator in this study could be potentially helpful to the field of simulation-based dental education.

There are certain limitations to the current prototype simulator. It allows only two degrees of freedom in mandibular movement. Additionally, two separate actuators were used for rotation and translation movements, resulting in two joints for these functions. Therefore, it would be better to develop a robotic simulator, fully simulating the TMJ and allowing more degrees of freedom. Furthermore, assessment research using a questionnaire should be conducted to evaluate the students' recognition and satisfaction regarding the practical reliability of the current simulator.

Conclusion

Although the upper-body prototype simulator was able to achieve the objectives, further advancements are still required to improve its efficiency and stability. Through continuous improvement and development, the simulation of the human body becomes more realistic, and it is expected to develop into a future-oriented dental education that improves student concentration and encourages them to consider how to communicate with patients.

References

1. Sachdeo A, Konfino S, Icyda RU, Finkelman MD, Gulati H, Arsenault P, Hanley JB. An analysis of patient grievances in a dental school clinical environment. J Dent Educ 2012;76:1317-22.
2. Rad FA, Otaki F, Baqain Z, Zary N, Al-Halabi M. Rapid transition to distance learning due to COVID-19: Perceptions of postgraduate dental learners and instructors. PLoS One 2021;16:e0246584.
3. Eckles RE, Meslin EM, Gaffney M, Helft PR. Medical ethics education: where are we? Where should we be going? a review. Acad Med 2005;80:1143-52.
4. Beemsterboer PL. Developing an ethic of access to care in dentistry. J Dent Educ 2006;70:1212-6.
5. Mossey PA, Newton JP, Stirrups DR. Scope of the OSCE in the assessment of clinical skills in dentistry. Br Dent J 2001;190:323-6.
6. Rodrigues P, Esteves A, Botelho J, Machado V, Zagalo C, Zorzal ER, Mendes JJ, Lopes DS. Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator. Comput Methods Programs Biomed 2022;221:106831.
7. Murbay S, Neelakantan P, Chang JWW, Yeung S. 'Evaluation of the introduction of a dental virtual simulator on the performance of undergraduate dental students in the pre-clinical operative dentistry course'. Eur J Dent Educ 2020;24:5-16.
8. Mirghani I, Mushtaq F, Allsop MJ, Al-Saud LM, Tickhill N, Potter C, Keeling A, Mon-Williams MA, Manogue M. Capturing differences in dental training using a virtual reality simulator. Eur J Dent Educ 2018;22:67-71.
9. de Boer IR, Lagerweij MD, Wesselink PR, Vervoorn JM. The effect of variations in force feedback in a virtual reality environment on the performance and satisfaction of dental students. Simul Healthc 2019;14:169-74.
10. Tanzawa T, Futaki K, Tani C, Hasegawa T, Yamamoto M, Miyazaki T, Maki K. Introduction of a robot patient into dental education. Eur J Dent Educ 2012;16:e195-9.

11. Tanzawa T, Futaki K, Kurabayashi H, Goto K, Yoshihama Y, Hasegawa T, Yamamoto M, Inoue M, Miyazaki T, Maki K. Medical emergency education using a robot patient in a dental setting. Eur J Dent Educ 2013;17:e114-9.
12. McDevitt WE, MacCarthy DJ, Dermody J, O'Sullivan M, Shanley DB. Learning a clinical method to identify a mandibular reference position. Eur J Dent Educ 1998;2:33-8.
13. McKee JR. Comparing condylar position repeatability for standardized versus nonstandardized methods of achieving centric relation. J Prosthet Dent 1997;77:280-4.
14. Peck CC, Murray GM, Johnson CW, Klineberg IJ. The variability of condylar point pathways in open-close jaw movements. J Prosthet Dent 1997;77:394-404.
15. Celic R, Jerolimov V, Knezovic Zlataric D. Relationship of slightly limited mandibular movements to temporomandibular disorders. Braz Dent J 2004;15:151-4.
16. Mohamed SE, Schmidt JR, Harrison JD. Articulators in dental education and practice. J Prosthet Dent 1976;36:319-25.
17. Kurth LE. Mandibular movement and articulator occlusion. J Am Dent Assoc 1949;39:37-46.
18. Hugger A, Hugger S, Ruge S, John D, Kordaß B. The rotation vs translation behavior during habitual opening and closing movements of the mandible and the relationship to movement paths of condylar points. Int J Comput Dent 2020;23:17-26.
19. Abe S, Noguchi N, Matsuka Y, Shinohara C, Kimura T, Oka K, Okura K, Rodis OMM, Kawano F. Educational effects using a robot patient simulation system for development of clinical attitude. Eur J Dent Educ 2018;22:e327-36.
20. Ahire M, Dani N, Muttha R. Dental health education through the brushing ROBOTUTOR: a new learning experience. J Indian Soc Periodontol 2012;16:417-20.
21. Newby JP, Keast J, Adam WR. Simulation of medical emergencies in dental practice: development and evaluation of an undergraduate training programme. Aust Dent J 2010;55:399-404.
22. Kinoshita H, Nagahata M, Takano N, Takemoto S, Matsunaga S, Abe S, Yoshinari M, Kawada E. Development of a drilling simulator for dental implant surgery. J Dent Educ 2016;80:83-90.
23. Nishino T. Swallowing as a protective reflex for the upper respiratory tract. Anesthesiology 1993;79:588-601.
24. Kohjitani A, Egusa M, Shimada M, Miyawaki T. Accumulated oropharyngeal water increases coughing during dental treatment with intravenous sedation. J Oral Rehabil 2008;35:203-8.
25. Hanamoto H, Kadono K, Boku A, Kudo C, Morimoto Y, Sugimura M, Niwa H. Both head extension and mouth opening impair the ability to swallow in the supine position. J Oral Rehabil 2014;41:588-94.
26. Cavalcanti BN, Otani C, Rode SM. High-speed cavity preparation techniques with different water flows. J Prosthet Dent 2002;87:158-61.
27. Lauer HC, Kraft E, Rothlauf W, Zwingers T. Effects of the temperature of cooling water during high-speed and ultrahigh-speed tooth preparation. J Prosthet Dent 1990;63:407-14.
28. Koster TJ, Timmerman MF, Feilzer AJ, Van der Velden U, Van der Weijden FA. Water coolant supply in relation to different ultrasonic scaler systems, tips and coolant settings. J Clin Periodontol 2009;36:127-31.
29. Matys J, Grzech-Leśniak K. Dental aerosol as a hazard risk for dental workers. Materials (Basel) 2020;13:5109.
30. Choi JJE, Chen J, Choi YJ, Moffat SM, Duncan WJ, Waddell JN, Jermy M. Dental high-speed handpiece and ultrasonic scaler aerosol generation levels and the effect of suction and air supply. Infect Control Hosp Epidemiol 2023;44:926-33.
31. Rolke R, Magerl W, Campbell KA, Schalber C, Caspari S, Birklein F, Treede RD. Quantitative sensory testing: a comprehensive protocol for clinical trials. Eur J Pain 2006;10:77-88.
32. Corah NL, O'Shea RM, Bissell GD, Thines TJ, Mendola P. The dentist-patient relationship: perceived dentist behaviors that reduce patient anxiety and increase satisfaction. J Am Dent Assoc 1988;116:73-6.
33. Lee M, Song Y, You M, Park SY, Ihm J. Dentists' attitudes toward patient-centered care and its predictors: a cross-sectional study in South Korea. BMC Oral Health 2023;23:75.
34. Lindauer SJ, Sabol G, Isaacson RJ, Davidovitch M. Condylar movement and mandibular rotation during jaw opening. Am J Orthod Dentofacial Or-

thop 1995;107:573-7.
35. Messerman T. A means for studying mandibular movements. J Prosthet Dent 1967;17:36-43.
36. Posselt U. Range of movement of the mandible. J Am Dent Assoc 1958;56:10-3.
37. Posselt U. Physiology of occlusion and rehabilitation. 2nd ed. Oxford; Blackwell Scientific; 1962. p. 41, 56, 181.
38. Li XY, Jia C, Zhang ZC. The normal range of maximum mouth opening and its correlation with height or weight in the young adult Chinese population. J Dent Sci 2017;12:56-9.
39. Park Y, Lee T, Seog M, Kim SO, Kim J, Kwon JS, Kang CM. An analysis of the temporomandibular joint range of motion and related factors in children and adolescents. Children (Basel) 2021;8:515.
40. Lewis RP, Buschang PH, Throckmorton GS. Sex differences in mandibular movements during opening and closing. Am J Orthod Dentofacial Orthop 2001;120:294-303.
41. Al-Dlaigan YH, Asiry MA. Maximum mouth opening in saudi adolescents. J Int Oral Health 2014;6:45-9.
42. Dario P, Guglielmelli E, Allotta B, Carrozza MC. Robotics for medical applications. IEEE Robot Autom Mag 1996;3:44-56.
43. Locsin RC. The co-existence of technology and caring in the theory of technological competency as caring in nursing. J Med Invest 2017;64:160-4.
44. Adel S, Zaher A, El Harouni N, Venugopal A, Premjani P, Vaid N. Robotic applications in orthodontics: changing the face of contemporary clinical care. Biomed Res Int 2021;2021:9954615.
45. Ahmad P, Alam MK, Aldajani A, Alahmari A, Alanazi A, Stoddart M, Sghaireen MG. Dental robotics: a disruptive technology. Sensors (Basel) 2021;21:3308.

치의학 교육을 위한 프로토타입 시뮬레이터의 개발

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목적. 이 연구의 목적은 치의학 교육을 위한 프로토타입 로봇 시뮬레이터를 제작하고, 하악운동을 시뮬레이션 할 수 있는지 여부를 테스트하며, 치과실습 중 자극에 대한 시뮬레이터의 반응 가능성을 평가하는 것이었다. **재료 및 방법.** 가상 시뮬레이터 모델은 cone-beam computed tomography (CBCT) 데이터를 사용하여 경조직을 구획화한 후 제작되었다. 시뮬레이터의 프레임은 polylactic acid (PLA) 소재를 사용하여 3D 프린팅 되었으며, 덴티폼과 실리콘 얼굴 스킨을 장착하여 모델을 형성하였다. 서보 액추에이터는 시뮬레이터의 움직임을 제어하는데 사용되었고, 다양한 센서들로 시뮬레이터의 반응을 생성하였다. 수위 센서가 반응하는 물의 양을 측정하기 위해 수위테스트가 수행되었다. 또한, 컴퓨터 시뮬레이션과 실제 모델을 통해 시뮬레이터의 하악운동과 하악운동 범위를 테스트하였다. **결과.** 프로토타입 로봇 시뮬레이터는 작동 장치, 전기 장치가 있는 상반신, 턱관절을 포함하는 머리 및 덴티폼으로 구성되었다. 시뮬레이터의 턱관절은 회전 및 병진 운동을 구현하면서 2자유도를 구동할 수 있었다. 수위 테스트에서 수위 센서의 특정 임계값은 10.35 ml였다. 컴퓨터 시뮬레이션과 실제 모델 모두에서 인간의 움직임을 모방하였고, 시뮬레이터의 하악운동 시 개구범위는 50 mm였다. **결론.** 효율성과 안정성을 개선하기 위해서는 더 많은 발전이 필요하지만, 본 상반신 프로토타입의 시뮬레이터는 향후 치과실습 교육에 잠재적으로 유용할 것으로 기대된다. (대한치과보철학회지 2023;61:257-67)

주요단어
치의학 교육; 하악운동; 로봇환자; 시뮬레이터

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원고접수일 2023년 7월 10일
원고최종수정일 2023년 7월 20일
원고채택일 2023년 7월 24일