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Original Article

Development of an Object Length Measurement System in a Virtual Reality Space for Medical Education

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Abstract

Purpose : This study aimed to develop a prototype caliper measurement tool that exists in real space to measure the length of three-dimensional (3D) virtual reality (VR) anatomical models with acceptable accuracy and reproducibility, particularly for medical education and training.

Methods : The measurement tool was constructed using a digital caliper with two object-tracking sensors to synchronize the positions of the virtual and real jaws. The accuracy and reproducibility for measuring virtual cubes (5, 10, 25, 50, and 100 mm) and three anatomical regions of VR models for vessel, skeleton, and organ were examined. Measurements for the virtual cubes and VR anatomical models were performed by one and two raters, respectively. The degree of agreement between measurements was evaluated using intraclass correlation coefficients (ICC).

Results : The developed tool effectively connected real and VR spaces. The measurement errors of the virtual cubes were within 0.5 mm or less for all virtual cube sizes. No statistically significant differences were observed between the errors for any of the virtual cube sizes. Alternatively, measurement errors were within 0.3 mm or less for all regions of VR anatomical models. No statistically significant differences were observed between the errors for the VR anatomical models. High degrees of intra- and inter-rater measurement reliabilities in terms of the ICC were 0.99 in both.

Conclusion : The developed prototype measurement tool was effective in a VR environment with measurement errors of less than 0.5 mm and reliable ICCs for the measurement of VR objects and VR anatomical structures, especially for medical education and training.

Key words : virtual reality, medical education, preoperative training, anatomical model, measurement tool

Introduction

Virtual reality (VR) technology has been applied to laparoscopic surgery training, such as cholecystectomy and hysterectomy[1][2], and in training for robotic surgery[3]. In clinical practice, VR technology has been applied not only for surgical training but also for surgical planning and simulation of surgical procedures[4]~[7]. Surgical planning requires a surgeon's spatial understanding of the anatomical structures, and three-dimensional (3D) visualization and measurement of the surgical target anatomy are essential for the surgeon[8]~[10]. The anatomical structures of the patient's specific surgical regions were also visualized three-dimensionally and measured using 3D-printed anatomical models. Size assessment of 3D-printed anatomical models is normally performed with direct measurements using a physical caliper or a ruler[11]~[13]. However, direct

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measurement is difficult to apply to virtual objects expressed in a virtual space. This is because of the vision occlusion of the real environment by a head-mounted display (HMD) to display the virtual environment. Virtual ruler tools within VR applications are typically used for virtual object size assessment. These tools are based on theoretical calculations in the virtual reality environments. Although virtual measurement tools for VR anatomical models are available on medical platforms equipped with VR application software, they are expensive and unavailable for convenient access14).

Various methods have been applied to measure 3D anatomical models in previous studies to overcome such problems. Preim et al. proposed an elaborate tool for measuring 3D human anatomy derived from medical images such as computed tomography (CT) and magnetic resonance (MR) image data15). They employed an interaction technique with a 3D image of human anatomy and a desktop-based 3D tool for measurement. The tool provides a more natural mechanism to measure 3D anatomical structures than 2D-image based measurement systems and enables the measurer's perceptual use of depth. However, these styles of interaction using a mouse are indirect measurements. Timonen et al. compared the conventional 2D measurements on the CT images of specimen bones using a picture archiving and communication system (PACS) interface with virtual measurements on the VR anatomical models derived from CT images and revealed that their virtual measurements had less measurement error than the 2D measurements16). Anik et al. compared actual measurements of real anatomical models with the virtual measurements of VR models derived from their CT image data and argued for the accuracy of the virtual measurement with its validity as a measurement method17). However, Aniks' virtual measurement is based on the controller interaction of line drawings on the VR anatomical model from the starting point to the end point of the measurement. Hence, the measurement is also an indirect procedure similar to mouse interaction, and has the issue of less effective utilization of the operator's intuitive perception of the structural depth.

Regarding the use of VR anatomical models employed as medical education resources, previous studies have assessed whether the human anatomy represented in VR could be substituted for a human subject18). However, the learning effects regarding the representation size of VR anatomical models and their measurement has not been sufficiently explored. Furthermore, no measurement tool has been developed based on a physical measuring device that can measure the size of VR anatomical models accurately. Developing a tool that can freely measure and evaluate the relationships between the size settings of VR models and the results of their representation in the VR space would be considered essential for these continued explorations.

This study aimed to develop a prototype of an object length measurement system for VR anatomical models using a digital caliper, which enables intuitive and direct measurement evaluation of the VR anatomical models represented in the VR space while wearing the HMD, and to discuss the possibility and significance of its application in clinical practice and medical education.

Materials and Methods

Requirements for VR measurement system in this study

Our study comprised the development of a prototype of a VR object length measurement system, creation of virtual cubes and VR anatomical models, and measurement experiments using the developed virtual jaws. To develop the system, the following five requirements were considered to clarify the differences between our developed system and the conventional VR measurement system.

(i) The system can be used while wearing the

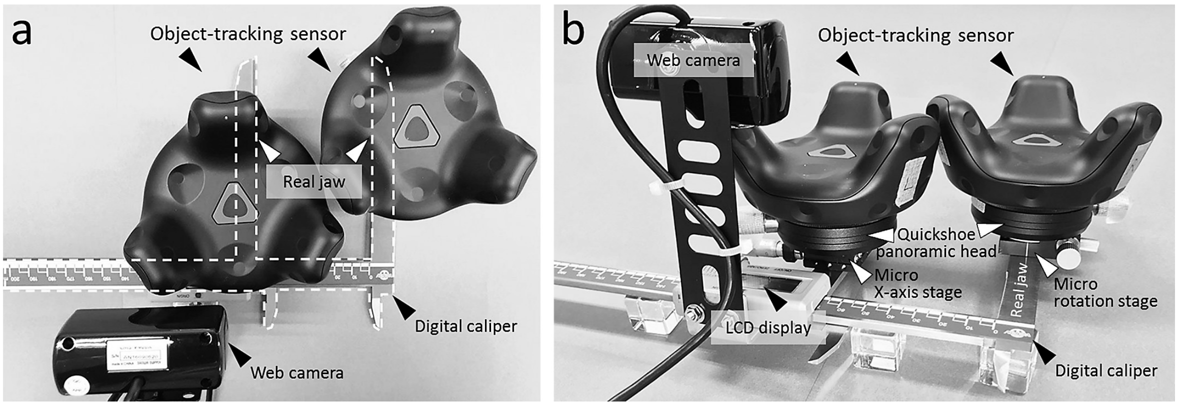

Fig. 1
a. Photograph that is taken from top of the "synchro-caliper." Dashed line indicates the shape of the digital caliper.
b. The instruments composing the synchro-caliper are mounted on the left and right real jaw in the following order: micro-X-axis or rotation stage, quickshoe panoramic head, and object-tracking sensor.
The web camera is fixed facing the LCD display, which is placed on the slider of a caliper.

HMD.

(ii) The system can measure the length of the VR anatomical model directly on a physical scale in real space.

(iii) Users should be able to check the length of the VR object in real-time in the VR space.

(iv) The system has sufficient accuracy and repeatability, similar to the typical caliper in real space.

(v) The system should be easy to measure and handle intuitively, similar to the caliper in real space.

VR measurement system development and VR space construction

A digital caliper (model E-LSM20B, Nakamura Mfg. Co., Ltd., Tokyo, Japan) was employed as the basis for the VR measurement system (Fig. 1a). The developed prototype system included two object-tracking sensors (Vive tracker, HTC Co., New Taipei, Taiwan), a web camera (model CMS-V40BK, SANWA SUPPLY INC., Okayama, Japan), a micro-X-axis stage (model Σ-207C, SIGMAKOKI CO., LTD, Tokyo, Japan), a micro-rotation stage (model KSP-256, SIGMAKOKI CO., LTD, Tokyo, Japan), and two quickshoe panoramic heads (model quickshoe panoramic head, INPON, China) (Fig. 1b). The object-tracking sensor tracks the real object's position coordinate with its motion in real space, and the tracked coordinate information is directly reproduced to the virtual object in the VR space. Hence, by attaching the sensor to the two real jaws of the digital caliper, the virtual jaws can be precisely synchronized with real jaws. Therefore, the developed measurement system was called "synchro-caliper" in this study. Another object-tracking sensor was used to link the coordinates of the virtual cube or the VR anatomical model to the measurement object (Fig. 2). In addition, the web camera was mounted facing the LCD display of the digital caliper, and the image from the camera was displayed on the HMD to check its length in the VR space (Fig. 1b). Micro stages and quickshoe panoramic heads were used for physical parallel alignment adjustment between the virtual jaws and for zero calibration. An HMD (HTC Vive, HTC Co., New Taipei, Taiwan) and a desktop personal computer (model G-Tune EGPI770G107DR30W10, MouseComputer Co., Tokyo, Japan) were used to visualize and manipulate the virtual objects in the VR space. The VR space and the measurement environment for the measurement experiments were generated using the game engine software, Unity Ver. 2018. 2. 13f1 (Unity Technologies, California, USA).

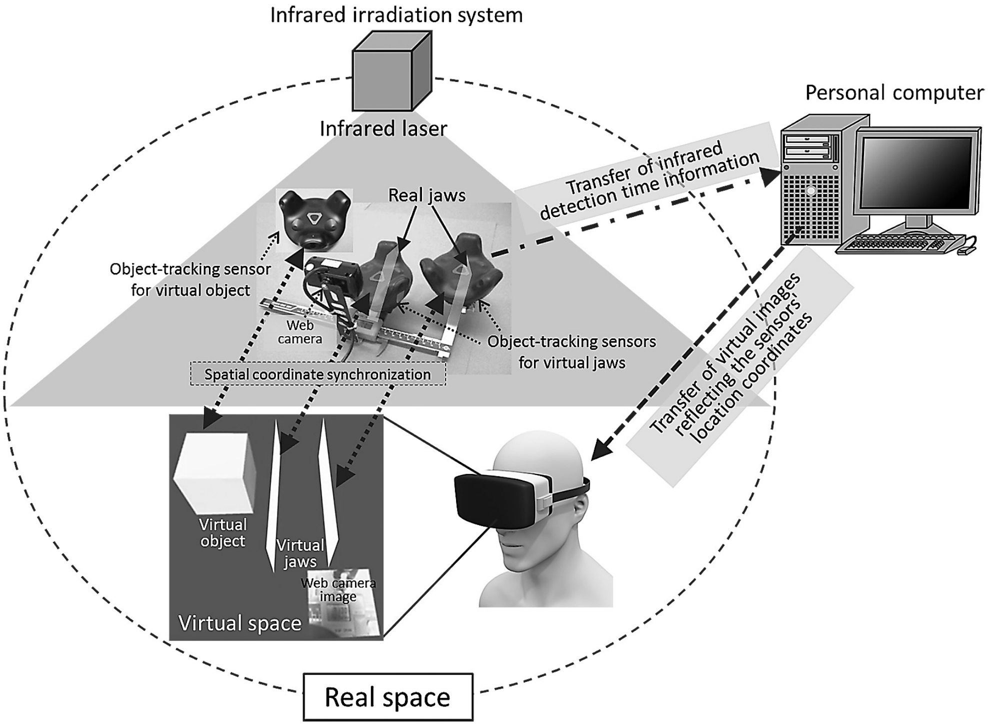

Fig. 2
Illustration of our operating principle of the measurement system.
The object-tracking sensor instantly transfers the infrared detection time information to a personal computer when it detects infrared irradiated from a fixed point. The software on the personal computer calculates the sensor position as coordinates in real space, based on the time information data received. The calculated coordinate positions are then reflected in real time as the positions of the virtual jaws and objects in the VR space to be displayed on the HMD.

Virtual cubes of five different sizes and three VR anatomical models (celiac artery, cervical spine, left kidney, and a pair of virtual jaws) were used in this study. For the measurement experiments, cubes of various sizes (5, 10, 25, 50, and 100 mm (Fig. 3a)) were created using the 3D computer-aided design software Fusion 360 (Autodesk, Inc., California, USA), and exported as the Unity compatible FBX file format[19]. These cubes were used to examine the fundamental measurement characteristics of the synchro-caliper, such as the measurement accuracy and repeatability. The VR anatomical models (Fig. 3 b, 3c, 3d) were created using the CT image data obtained from the OsiriX DICOM Image Library (https://www.osirix-viewer.com/resources/dicom-image-library/) and an image computing software, 3D Slicer Ver. 4.11 (https://www.slicer.org/). Finally, the VR anatomical models were cropped and exported in stereolithography (STL) file format[20][21]. To show the measurement region, a pair of plates was implanted parallel to the measurement target anatomical region as measurement land marker plates using the 3D object design and optimization software Netfabb (Autodesk, Inc. California, USA). These STL models were finally converted to FBX format models in a 3D computer graphics software Blender (Blender Foundation, Amsterdam, Netherlands). Alternatively, a pair of virtual jaws for the synchro-caliper was 3D modeled using Fusion 360 as rectangular thin plates and exported in the FBX file format. In addition, the virtual jaws for length measurement were designed to notify the contact between the virtual jaw and virtual object to be measured by the color change of the virtual jaw itself.

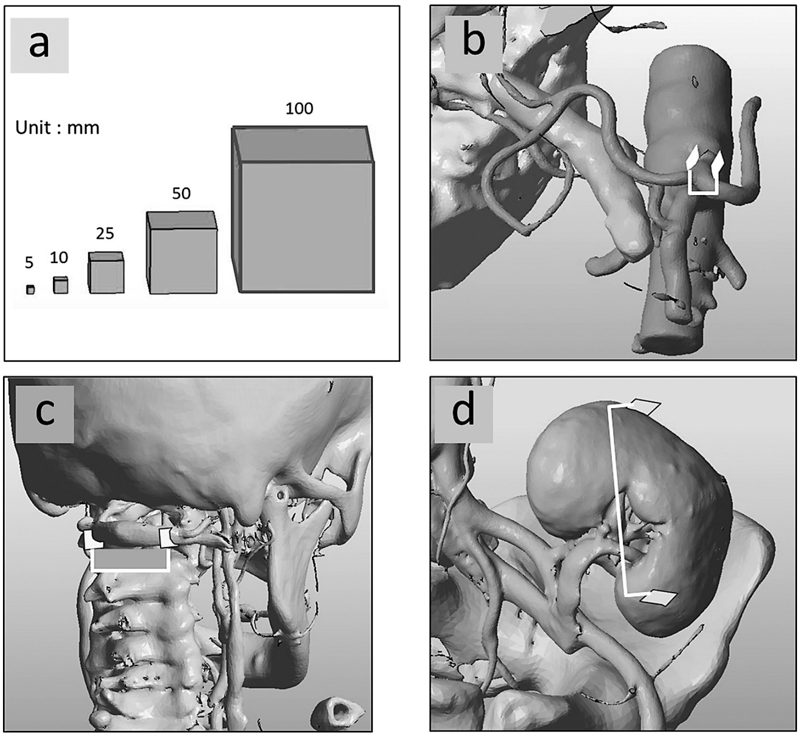

Fig. 3
a. Virtual cubes used in measurement experiments.
b. Frontal view of the VR abdominal aorta model, including the celiac artery. The white bracket indicates the region of the celiac artery to be measured.
c. Posterior view of VR skull and cervical spine models. The white bracket indicates the region of the posterior arch of the atlas to be measured.
d. Oblique view of the VR model of the transplanted kidney. The white bracket indicates the region of the longitudinal length of the kidney to be measured.

Measurement experiments and statistical analysis

Zero-setting of the synchro-caliper was performed immediately prior to the virtual cube measurement. This was accomplished by physically fine-tuning the rotation and movement of object-tracking sensors that synchronized the virtual jaws. The contact notification function on the virtual jaws described in the previous section was used to determine the correct parallel alignment and contact. Next, parallel alignments were performed between the facing surfaces of the virtual cube and virtual jaws on both sides. Thereafter, the length of the cube was measured at the positions of contact between the virtual jaws and the facing virtual cube surface while wearing the HMD. The measured lengths were recorded values presented on the LCD in the VR space. In this study, measurement experiments using the anatomical models were conducted to simulate the environment in which measurement system would be used, as expected in medical education and training (Fig. 4a). The zero-setting of the synchro-caliper was also performed for the measurement of the VR anatomical regions. Measurements were taken of the lengths between the land marker plates in the VR anatomical regions. In the measurement experiment, parallel alignments were performed between the facing surfaces of the land marker plates and virtual jaws on both sides. Subsequently, the length between the land marker plates was measured at the positions where the contact between the virtual jaws and the facing land marker plate was measured. The measured lengths were also recorded as values on the LCD in the VR space

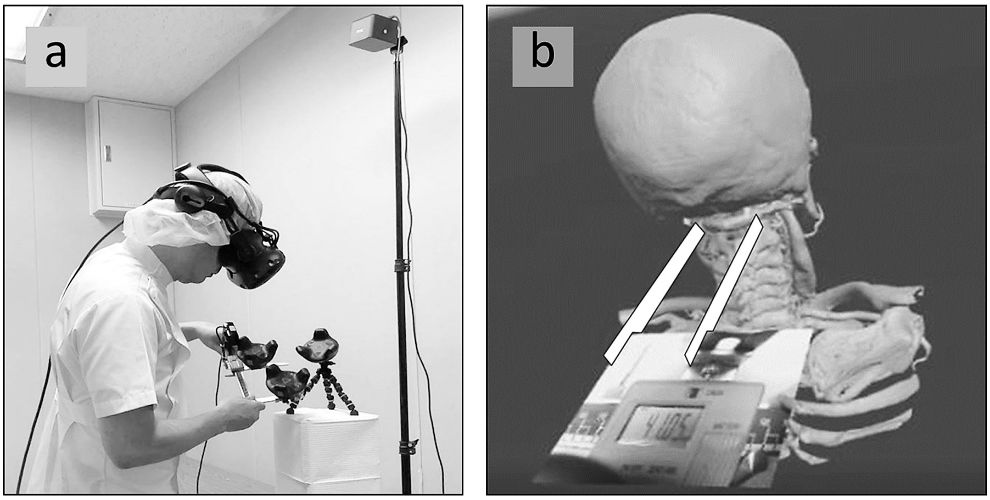

Fig. 4
A Photograph of the rater wearing the head-mounted display and an example of image view in the VR space.

a. VR equipment placement during the measurement experiment and the user during measurement task.

b. The captured image presents the VR image visualized on the head-mounted display while measuring the posterior arch of the atlas. The pair of long white rectangular plates indicates the virtual jaws of the synchro-caliper. The measurements presented on the LCD display by the digital caliper were captured with a web camera and displayed on the screen within the VR space in real-time.

Table 1 Summary of raters' backgrounds

rater	A	B	C
specialty	radiological technology	colorectal surgery	spine surgery
years of specialty experience	31	10	30
experience of VR technology in the past	yes	no	no

(Fig. 4b). In this study, to eliminate the unconscious bias of the rater in length measurement, the LCD displaying the measured length was covered until confirmation of the contact determination between the virtual jaw and the virtual object.

The ground-truth dimensions of the VR anatomical regions were measured as the lengths between the land marker plates in each anatomical region using 2-D desktop-based 3-D measurement tools in the Netfabb. This software can perform structural analysis of the created 3D models and verify the accuracy of its shape and size. In the measurement experiments, 3 operators were defined as raters A, B, and C, respectively (Table 1). Rater A performed measurements repeated 10 times per day for 12 months on 3 independent days for each cube. For the ground-truth dimensions of the three VR anatomical regions, rater C performed measurements 30 times in a day for averaging to determine the truth. In contrast, for each VR anatomical region, raters A and B performed the measurements. Rater A repeated this measurement 10 times per day for independent 3 days, and rater B repeated the measurement 10 times for only one day.

The measurement errors of the virtual cubes

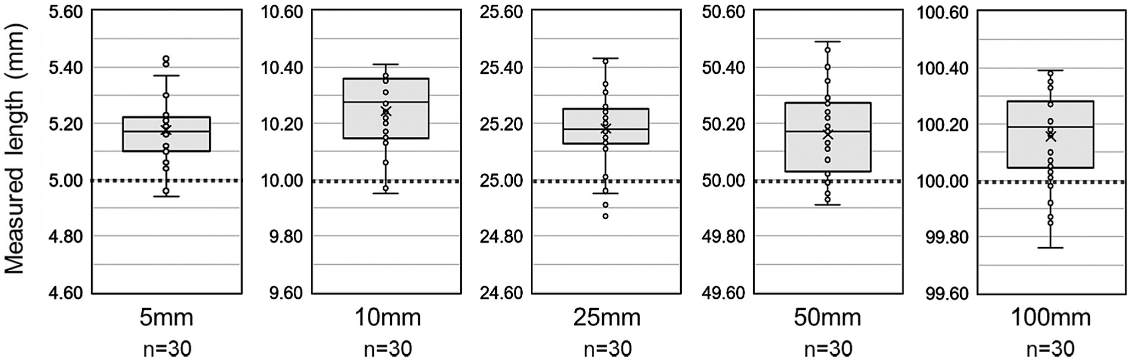

Fig. 5

The distribution of the measurements for various sizes of cubes.
The horizontal dashed lines drawn on each graph indicate the ground-truth dimensions for the measured cubes.

Table 2 Summary of the measurements for the cubes

Cube size	5 (n=30)	10 (n=30)	25 (n=30)	50 (n=30)	100 (n=30)
Max. length	5.43	10.41	25.43	50.49	100.39
Min. length	4.94	9.95	24.87	49.91	99.76
Average	5.18	10.24	25.18	50.16	100.16
Max. percentage error (%)	8.60	4.10	1.72	0.98	0.39

Unit : mm

and VR anatomical regions were calculated using Eq. (1) and (2), respectively. The percentage error was calculated using Eq. (3) and (4). The Jarque-Bera test[22] was used to examine the normality of the data for measurement errors. Finally, the measurement error analysis was examined using multiple comparison tests for the analysis of variance. For all statistical analyses, the level of significance was set at $p < 0.05$.

The intra-rater reliabilities in the virtual cube and the VR anatomical region measurements were evaluated using the intraclass correlation coefficients[23] namely ICC (1, 1), ICC (1, 3) and ICC (2, 1).

Measurement error of the virtual cube
= Measured length between opposing virtual cube faces-Designed virtual cube size (1)

Measurement error of the VR anatomical region
= Measured length between land marker plates-Ground truth dimension of the VR anatomical region (2)

Percentage error of the virtual cube

$$= \frac{\textit{ABSOLUTE(Measured length between opposing virtual cube faces–Designed virtual cube size)}}{\textit{Designed virtual cube size}} \times 100 \quad (3)$$

Percentage error of the VR anatomical region

$$= \frac{\textit{ABSOLUTE(Measured length between lamd marker plates–Ground truth dimension of the VR anatomical region)}}{\textit{Ground truth dimension of the VR anatomical region}} \times 100 \quad (4)$$

Results

The average lengths of each measurement for virtual cubes of 5, 10, 25, 50, and 100 mm were 5.18 mm, 10.24 mm, 25.18 mm, 50.16 mm, and

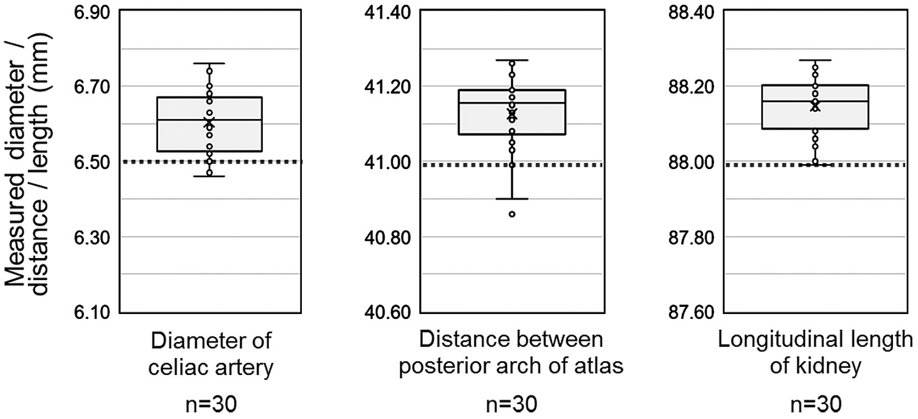

Fig. 6
The distribution of the measurements for the VR anatomical regions.
The horizontal dashed lines drawn on each graph indicate the ground-truth dimensions of the measured VR anatomical regions.

Table 3 Summary of the measurements for the VR anatomical regions

Anatomical region	Diameter of celiac artery (n=30)	Distance between posterior arch of atlas (n=30)	Longitudinal length of kidney (n=30)
Ground-truth dimension	6.50	40.99	87.99
Max. diameter/distance/length	6.76	41.27	88.27
Min. diameter/distance/length	6.46	40.86	87.99
Average	6.60	41.13	88.15
Max. percentage error (%)	3.94	0.67	0.32

Unit : mm

100.16 mm, respectively. The measurement errors of the virtual cubes were within 0.5 mm or less for all virtual cube sizes (Fig. 5). The maximum percentage errors of the virtual cubes were 8.6%, 4.1%, 1.72%, 0.98%, and 0.39%, respectively, with the smallest virtual cube sizes having the largest values (Table 2).

For the VR anatomical models, the average lengths of measurements against the ground-truth dimensions defined in the VR anatomical regions were 6.5 mm vs. 6.6 mm for the celiac artery diameter, 40.99 mm vs. 41.13 mm for the distance between the posterior arch of atlas, and 87.99 mm vs. 88.15 mm for the longitudinal length of the kidney. The measurement errors were within 0.3 mm or less for all anatomical regions displayed in the VR space (Fig. 6), (Table 3).

The normality test results revealed that the assumption of normality for parametric testing was valid for all measurement errors. Therefore, Bonferroni/Dunns' parametric multiple comparison tests[24)] were adopted for significance difference tests of the measurement errors for the virtual cubes and VR anatomical regions, respectively. There were no statistically significant differences in the measurement errors between the different sizes of the virtual cubes or between the VR anatomical regions. These results indicate that the measurement errors were constant and unaffected by the dimensions of the virtual objects.

Alternatively, measurement reproducibility in terms of ICCs indicated excellent reproducibility of 0.99 both in intra- and inter-rater measurements. These results revealed the high accuracy and reproducibility of the measurements, which satisfied the requirements of the measurement system to be developed.

Discussions

A system named "synchro-caliper" was developed, which combines a digital caliper, two object-tracking sensors, and a web camera. The synchro-caliper allowed the direct measurement of the VR objects in the VR space by physical dimensions in real space. The measurement errors of the synchro-caliper were revealed to be less than the 0.5 mm error range for the length measurements of the VR objects across the size range of 5 mm to 100 mm. Since contact detection used for the measurements detects even if one place between the virtual jaw and the virtual object is touched, the influence of the approach from outside the virtual jaw tended to be overestimated in our results (Figs. 5–6, Table 2–3). Furthermore, excellent measurement reproducibility was demonstrated, as indicated by the ICCs for the intra- and inter-rater reliabilities of the length measurements of the VR objects. Therefore, our proposed prototype measurement system for length has the potential to be adapted to medical education and preoperative planning applications of VR technology, which are becoming increasingly more practical.

Since measurement accuracy is required for medical applications of VR anatomy measurement, previous studies have been conducted to develop measurement tools and/or to evaluate the measurement accuracy with VR anatomy measurements15)25). In the latest reports, the measurement accuracy of virtual measurement application tools was evaluated based on comparisons between the actual measurements on human specimen bones and the virtual measurements on the VR anatomical models were created using the CT images of the specimen bones16)17). Anik et al. reported that the measurement errors of virtual measurements on the VR anatomical model of the specimen bone included 93.8% of the measurements, within an error range of 1.27 mm17). Timonen et al. reported that the maximum percentage of the mean measurement error was 4.22% in their measurement experiments using the VR specimen bone model16). Their results may include the effects of voxel size owing to the slice thickness of the CT imaging and threshold settings for constructing the 3D surface image from the CT image data. In this study, the measurement errors of the VR anatomical regions were within the error range of 0.3 mm, and the maximum percentage of the mean measurement error was 1.54%, which was smaller than the measurement errors reported in previous studies. Thus, our lower error compared with previous reports may be owing to the ground-truth dimension, which is determined based on the created VR anatomical model rather than the length measured in the actual object by Anik's method.

Previously developed and commercially available virtual measurement tools were used to calculate the distances based on the vertex coordinate information of the triangular mesh26) that forms the surface of the VR object. Thus, in the measurement of the VR anatomical model, it is indispensable to set measurement points on the surface of the triangular mesh, and the virtual measurement is limited to linear distance measurement between two points only on the surface of the VR anatomical model. In contrast, the proposed synchro-caliper uses virtual jaws for length measurement in the VR space, so it is not necessary to set the measurement points on the VR object. This significant feature of the synchro-caliper is expected to be effective in preoperative planning, as described below. For example, surgeons in total hip arthroplasty need to know the distance between the center of the femoral head and femoral axis as an offset of patient characteristic27). Furthermore, the proposed measurement system would be effective even for internal anatomical structures, such as arteriovenous vessels, portal vein, and bile ducts in the liver, to be measured by moving the virtual jaws directly into the liver. The developed tool can penetrate bones or organs. This penetration function is unique and unavailable in conventional virtual measurement methods. Therefore, it is expected that it can expand the application of the measurement of human anatomy represented in the VR space and increase its usefulness in clinical practice.

We believe that the system developed with the synchro-caliper has no mouse operation such as a personal computer and intuitive operability, allowing the user to concentrate on the operation in the VR space while wearing the HMD. It also has the same tactile and handling characteristics as real calipers. In a previous study, Wang et al. demonstrated that providing tactile feedback of physical objects to examine subjects experiencing VR space improved the three-dimensional interaction effects for manipulating and working with virtual objects28). It is therefore necessary to further investigate the potentiality of the tactile perception and operability of the synchro-caliper, which has the same perception as the digital caliper and may have a significant effect on the measurement accuracy and reproducibility compared with the mouse-like measurement operations using the conventional controller.

VR technology has a high affinity for anatomy education and enhances learning effects, and VR anatomical models can facilitate learners' understanding of 3D relationships with human anatomy29)~34). Moreover, VR anatomical models provide significant support for anatomy education in countries where access to human cadaveric specimens is not available for religious reasons or insufficient human dissection bodies are not adequately prepared35)36). The 3D human anatomical models based on VR technology have been regarded as complementary and reinforcing tools for anatomy education, and have a significant advantage of repeatable learning, as well as simulation learning of medical procedures33). In anatomy education, 3D-printed anatomical models are used as teaching materials37). The usefulness of 3D-printed anatomical models for surgical planning has also been reported11)~13). While 3D-printed anatomical models have the benefit of being hand-touchable, in some cases, the print size has been scaled down to reduce cost and print time. However, full-scale 3D-printed anatomical models are required for medical education and clinical practice because scale-modified 3D-printed models may not provide observers with an accurate understanding of the defects in anatomical structures or the actual size of diseased lesions38). Furthermore, it has been reported that if the learning environment in medical education does not allow medical students to access human cadaveric specimens in the curriculum, using an equivalent size of real human anatomy for 3D-printed models is important to prevent misinterpretation of anatomical structure sizes37). As for VR anatomical models, the most significant feature is the possibility of freely changing the scale of the anatomical models while wearing the HMD. However, from the perspective of the accurate understanding of the human anatomy size, the reproduction of the VR anatomical models in the "full-scale" as well as that of the 3D-printed anatomical models in the "full-scale" are equally important. As direct measurement of the anatomical structures reproduced by the 3D-printed models with calipers and rulers is beneficial for the accurate understanding of the human anatomy, the direct measurement of the VR anatomical models with the synchro-caliper can be expected to have significant benefits in human anatomy learning as well.

With the developed measurement system, it is possible to accurately measure the length of the anatomical structure while wearing the HMD. This has the effect of allowing you to experience the size of an object through VR anatomical region length measurement in VR simulation training or preoperative planning. Furthermore, we believe that the developed measurement system can be expanded in medical education as virtual preoperative training based on a full-scale reproduced anatomical model.

This study had several limitations. The first limitation was the maximum measurement range of 100 mm for the synchro-caliper. The system must be developed to cover measurement ranges longer than 100 mm. The second limitation was the weight of the synchro-caliper. Its total weight of 650 g places a burden on the user to ensure handling stability. The major reason for the heavy weight is the two object-tracking sensors. Therefore, the issue of weight must be addressed through weight reduction. If smaller and lighter object-tracking sensors or substitutable controllers were developed, the length measurement system would be more practical. The third limitation was not testing small structures with 5 mm or less such as nerves and vessels for microsurgery. Continued research is needed to ensure measurement accuracy in actual clinical use. Another limitation was VR sickness caused by wearing the HMD. In this study, no VR sickness symptoms were observed in all raters. However, VR sickness is an issue that requires verification for the safe and effective use of VR technology.

Declarations

The institutional research ethics committee was exempted from reviewing this study because it employed anonymized CT image data included in the OsiriX DICOM image library from a website authorized to be used for research and educational purposes. Informed consent was obtained from all individual participants after we fully explained the purpose of this study and the experiment methods.

Conclusion

A prototype of the length measure system called “synchro-caliper” has developed, which enables directly measuring and assessing the VR anatomical model while wearing the HMD. We conclude that the length measurement with high accuracy and reproducibility in the VR space was demonstrated, and that the system could be an important tool in medical education and clinical practice.

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References

1) Thompson JR, Leonard AC, Doarn CR, Roesch MJ and Broderick TJ : Limited value of haptics in virtual reality laparoscopic cholecystectomy training. Surg Endosc. 25 : 1107-1114, 2011.

2) Goderstad JM, Sandvik L, Fosse E and Lieng M : Development and validation of a general and easy assessable scoring system for laparoscopic skills using a virtual reality simulator. European Journal of Obstetrics & Gynecology and Reproductive Biology : X. 4 : 100092. doi : 10.1016/j.eurox. 2019. 100092, 2019.

3) Watkinson W, Raison R, Abe T, Harrison P, Khan S, Van der Poel H, Dasgupta P and Ahmed K : Establishing objective benchmarks in robotic virtual reality simulation at the level of a competent surgeon using the RobotiX Mentor simulator. Postgraduate Medical Journal. 94 : 270-277, 2018.

4) Badash I, Burtt K, Solorzano CA and Carey JN : Innovations in surgery simulation : a review of past, current and future techniques. Annals of Translational Medicine. 4 : 453. doi : 10.21037/atm. 2016. 12. 24, 2016.

5) Shirk JD, Kwan L and Saigal C : The Use of 3-Dimensional, Virtual Reality Models for Surgical Planning of Robotic Partial Nephrectomy. Urology. 125 : 92-97, 2019.

6) Kockro RA, Killeen T, Ayyad A, Glaser M, Stadie A, Reisch R, Giese A and Schwandt E : Aneurysm Surgery with Preoperative

Three-Dimensional Planning in a Virtual Reality Environment : Technique and Outcome Analysis. World Neurosurgery. 96 : 489-499, 2019.

7) Boedecker C, Huettl F, Saalfeld P, Paschold M, Kneist W, Baumgart J, Preim B, Hansen C, Lang H and Huber T : Using virtual 3D-models in surgical planning : workflow of an immersive virtual reality application in liver surgery. Langenbeck's Archives of Surgery. 406 : 911-915, 2021.

8) Reitinger B, Bornik A, Beichel D and Schmalstieg D : Liver Surgery Planning Using Virtual Reality. IEEE Computer Graphics and Applications. 26 : 36-47, 2006.

9) Zhao L, Patel PK and Cohen M : Application of Virtual Surgical Planning with Computer Assisted Design and Manufacturing Technology to Cranio-Maxillofacial Surgery. Archives of Plastic Surgery 39 : 309-316, 2012.

10) Chen Y, Li H, Wu D, Bi K and Liu C : Surgical planning and manual image fusion based on 3D model facilitate laparoscopic partial nephrectomy for intrarenal tumors. World Journal of Urology. 32 : 1493-1499, 2013.

11) Adolphs N, Liu W, Keeve E and Hoffmeister B : Craniomaxillofacial surgery planning based on 3D models derived from Cone-Beam CT data. Computer Aided Surgery. 18 : 101-108, 2013.

12) Shirakawa T, Koyama Y, Mizoguchi H and Yoshitatsu M : Morphological analysis and preoperative simulation of a double-chambered right ventricle using 3-dimensional printing technology. Interactive CardioVascular and Thoracic Surgery. 22 : 688-691, 2016.

13) Wake N, Rude T, Kang SK, Stifelman MD, Borin JF, Sodickson DK, Huang WC and Chandarana H : 3D printed renal cancer models derived from MRI data : application in pre-surgical planning. Abdominal Radiology. 42 : 1501-1509, 2017.

14) Clark AD, Barone DG, Candy N, Guilfoyle M, Budohoski K, Hofmann R, Santarius T, Kirollos R and Trivedi RA : The Effect of 3-Dimensional Simulation on Neurosurgical Skill Acquisition and Surgical Performance : A Review of the Literature. Journal of Surgical Education. 74 : 828-836, 2017.

15) Preim B, Tietjen C, Spindler W and Peitgen HO : Integration of Measurement Tools in Medical 3d Visualizations. Proceedings of the conference on Visualization '02 : 21-28, 2002.

16) Timonen T, Dietz A, Linder P, Lehtimäki A, Löppönen H, Elomaa AP and Mustajärvi M : The effect of virtual reality on temporal bone anatomy evaluation and performance. European Archives of Oto-Rhino-Laryngology. 279 : 4303-4312, 2021.

17) Anik AA, Xavier BA, Hansmann J, Ansong E, Chen J, Zhao L and Michals E : Accuracy and Reproducibility of Linear and Angular Measurements in Virtual Reality : a Validation Study. Journal of Digital Imaging. 33 : 111-120, 2020.

18) Zhuoshu Li, Zixin Li, Cheng Peng, Mingyi Zhao and Qingnan He : A Bibliometric Analysis of Virtual Reality in Anatomy Teaching Between 1999 and 2022. Frontiers in Education. 7 : 874406. doi : 10.3389/feduc. 2022. 874406, 2022.

19) Autodesk FBX Software Developer Kit. Retrieved August 18, 2022 from https://www.autodesk.com/developer-network/platform-technologies/fbx-converter-archives

20) 3D SYSTEMS What Is An STL File?. Retrieved August 18, 2022 from https://www.3dsystems.com/quickparts/learning-center/what-is-stl-file

21) Marro A, Bandukwala T and Mak W : Three-Dimensional Printing and Medical Imaging : A Review of the Methods and Applications. Current Problems in Diagnostic Radiology. 45 : 2-9, 2016.

22) Jarque CM and Bera AK : A Test for Normality of Observations and Regression Residuals. International Statistical Review. 55 : 163-172, 1987.

23) Weir JP : Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res. 19 : 231-241, 2005.

24) Dunn OJ : Multiple Comparisons among Means. J Am Stat Assoc. 56 : 52-64. 1961.

25) Wheeler G, Deng S, Pushparajah K, Schnabel JA, Simpson JM and Gomez : Virtual linear measurement system for accurate quantification of medical images. Healthc Technol Lett. 6 : 220-225, 2019.

26) Laval PB : Mathematics for Computer Graphics-Barycentric Coordinates. Kennesaw State University, Tech. Rep : 1-9, 2003.

27) Lecerf G, Fessy MH, Philippot R, Massin P, Giraud F, Flecher X, Girard J, Mertl P, Marchetti E and Stindel E : Femoral offset : Anatomical concept, definition, assessment, implications for preoperative templating and hip arthroplasty. Orthop Traumatol-Sur. 95 : 210-219, 2009.

28) Wang Y and MacKenzie CL : The Role of

Contextual Haptic and Visual Constraints on Object Manipulation in Virtual Environments. Proceedings of the SIGCHI conference on Human Factors in Computing Systems. 2 : 532-539, 2000.

29) Jang S, Vitale JM, Jyung RW and Black JB : Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. Computers & Education. 106 : 150-165, 2017.

30) Duarte ML, Santos LR, Guimarães Júnior JB and Peccin MS : Learning anatomy by virtual reality and augmented reality. A scope review : Apprentissage de l'anatomie par la réalité virtuelle et la réalité augmentée. Morphologie. 104 : 254-266, 2020.

31) Nakai K, Terada S, Takahara A, Hage D, Tubbs RS and Iwanaga J : Anatomy education for medical students in a virtual reality workspace : A pilot study. Clin Anat. 35 : 40-44, 2022.

32) Pringle Z and Rea PM : Do Digital Technologies Enhance Anatomical Education?. Practice and Evidence of Scholarship of Teaching and Learning in Higher Education. 13 : 2-27, 2018.

33) Chen S, Zhu J, Cheng C, Pan Z, Liu L, Du J, Shen X, Shen Z, Zhu H, Liu J, Yang H, Ma C and Pan H : Can virtual reality improve traditional anatomy education programmers? A mixed methods study on the use of a 3D skull model. BMC Medical Educ. 20 : 395, 2020.

34) Meyer ER and Cui D : Anatomy Visualizations Using Stereopsis : Assessment and Implication of Stereoscopic Virtual Models in Anatomical Education. Biomedical Visualisation. 6 : 117-130, 2020.

35) Naidoo N, Al-Sharif GA, Khan R, Azar A and Omer A : In death there is life : perceptions of the university community regarding body donation for educational purposes in the United Arab Emirates. Heliyon. 7 : e07650, 2021.

36) Karbasi Z and Kalhori SRN : Application and evaluation of virtual technologies for anatomy education to medical students : A review. Med J Islamic Repub Iran. 34 : 163, 2020.

37) Smith CF, Tollemache N, Covill D and Johnston M : Take Away Body Parts! An Investigation into the Use of 3D-Printed Anatomical Models in Undergraduate Anatomy Education. Anat Sci Educ. 11 : 44-53, 2018.

38) Lau I and Sun Z : Three-dimensional printing in congenital heart disease : A systematic review. J Med Radiat Sci. 65 : 226-236, 2018.

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（和文抄録）

医学教育のための仮想現実空間に表現した物体長計測システムの開発

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【目的】本研究は，head-mounted display（HMD）装着下でバーチャルリアリティ（VR）空間に表現したVR解剖モデルの直接的な計測評価が可能なデジタルノギスを利用した長さ計測システムのプロトタイプを開発し，計測の正確さと再現性を評価することで，医学・医療分野での活用の可能性と意義を考察することを目的とした．

【方法】実物体と仮想物体の位置・動きを同期するセンサで，現実空間のデジタルノギスのjawとVR空間の仮想jawとを紐付け，VR空間で使用できる長さの計測システムを開発した．この計測システムの評価は，一辺が5，10，25，50，100 mmの仮想キューブと，VRで表現した三つのVR解剖モデル（血管，骨格，臓器）に対して行った．キューブは1名の被験者による計測，VR解剖モデルは2名の被験者による計測を行い，結果は，キューブとVR解剖モデルに対する計測誤差とその統計的分析により評価した．また，被験者内の計測の信頼性と被験者間の計測の信頼性を，級内相関係数（intraclass correlation coefficients：ICC）を求め評価した．

【結果】開発した計測システムは，現実空間のデジタルノギスのjawとVR空間の仮想jawが連動し，HMD装着下でVR空間上に表現した物体の長さを計測できた．キューブの計測誤差は，すべてのキューブサイズで0.5 mm以内であった．また，各キューブサイズの計測誤差間には統計的有意差を認めなかった．VR解剖モデルの計測誤差は，すべての解剖部位で0.3 mm以内で，各VR解剖モデルの計測誤差の間にも統計的有意差を認めなかった．被験者内および被験者間の計測の信頼性（ICC）はともに0.99と十分に高い値を示した．

【結論】HMD装着下でVR解剖モデルの直接的な計測評価が可能な長さ計測システムのプロトタイプを開発でき，医学・医療分野での活用の可能性がある．

キーワード：仮想現実，医学教育，手術トレーニング，解剖モデル，物体長計測システム