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3D imaging and body measurement of riding horses using four scanners simultaneously

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Although there have been advances in the technology for measuring horse body size with stereoscopic three-dimensional (3D) scanners, previously reported methods with a single scanner still face a significant challenge: the time necessary for scanning is too long for the horses to remain stationary. This study attempted to scan the horse simultaneously from four directions using four scanners in order to complete the scans in a short amount of time and then combine the images from the four scans on a computer into one whole image of each horse. This study also compared body measurements from the combined 3D images with those taken from conventional manual measurements. Nine riding horses were used to construct stereoscopic composite images, and the following 10 measurements were taken: height at the withers, back, and croup; chest depth; width of the chest (WCh), croup, and waist; girth circumference, cannon circumference (CaC), and body length. The same 10 measurements were taken by conventional manual methods. Relative errors ranged from −1.89% to 7.05%. The correlation coefficient between manual and 3D measurements was significant for all body measurements ($P<0.01$) except for WCh and CaC. A simple regression analysis of all body measurements revealed a strong correlation ($P<0.001$, $R^2=0.9994$, root-mean-square error=1.612). Simultaneous scanning with four devices from four directions reduced the scanning time from 60 sec with one device to 15 sec. This made it possible to perform non-contact body measurements even on incompletely trained horses who could not remain stationary for long periods of time.

Keywords: *body measurement, composite stereoscopic image, conformation, horse, three-dimensional scan*

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Body measurement is extremely important for horses, since the size of a horse is considered to be an indicator of its ability and soundness. For this reason, many sites should be measured, and measurements should be taken multidimensionally because the growth of an organism is three-dimensional (3D) [14]. However, it is difficult and time-consuming to accurately measure many sites manually. Therefore, there is a need to develop new technologies to easily provide accurate measurements.

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Recently, there have been advances in the technology for acquiring stereoscopic images with a 3D scanner, even for large animals such as cattle [4, 5, 7, 8] and horses [15]. These advances facilitate the measurement of multiple sites with a single image and enable non-contact measurement. However, since specialized equipment and advanced data processing technologies, such as filtering and deep learning, were required in the above studies, it would be beneficial to develop a technique that could easily and accurately measure body size on-site. We recently developed a method to measure the sizes of horses using a highly versatile tablet-type 3D scanner [12]. Our previously reported method with a single scanner did not have accuracy problems, but significant methodological challenges remained. The method of scanning with a single device requires one min for one person to walk around the horse while moving the device up and down. The object is supposed to remain stationary, but one min is too long for a horse to remain stationary. Completing a scan within an amount of time short enough to allow the horse to stand still remains a challenge.

The present study attempted to shorten the measuring time by splitting up the imaging range among multiple 3D scanners. The horses were scanned with four devices simultaneously from four different angles: left cranial view, left caudal view, right cranial view, and right caudal view. Therefore, 3D images were taken from four directions simultaneously, and the images were combined to complete a stereoscopic image of the entire body. To assess this methodology, first, the accuracy of the 3D composite image was evaluated by comparing the measured values for each body part in the composite 3D image with the measured values obtained by conventional manual measurements. Next, the accuracy of the method using the four devices developed in this study was compared with the already reported method using a single device. Finally, the potential applications of the method using the four devices were discussed by comparing the differences in measurement methods and measurement times between the four-device method and one-device method.

Materials and Methods

The Ethics Committee of the Kitasato University School of Veterinary Medicine, Japan, approved this study (20-034).

Horses

A total of 9 riding horses (two mares and seven geldings), consisting of 7 thoroughbreds and 2 crossbreeds (mix × Haflinger and Haflinger × Japanese native horse), were studied. The horses were 4–19 years of age (mean ± standard deviation (SD), 14.1 ± 5.0 years), and their mean body weight (BW; mean ± SD) was 541.8 ± 43.4 kg. They were routinely used as riding horses for the equestrian team of Kitasato University or as scientific research animals. They were in good condition and well trained.

Experimental period

Measurements were taken in September and October 2021. Manual measurements and 3D scanning were performed on the same day for each horse. There was a maximum of 17 days between body measurement and weight measurement.

Conventional manual measurements

The horses were hitched to posts at a wash rack without a handler and stood in a standard position without a rider. After confirming that the entirety of the hooves of all four limbs were in contact with the ground, the measurements were performed. To reduce possible variation, conventional manual measurements were always carried out by the same animal keeper, as noted in the study by Pérez-Ruiz *et al.* [15]. We measured equine conformation by the same method noted in our previous study [12]. The following manual measurements were obtained:

Height at the withers (HWi)
Height at the back (HBa)
Height at the croup (HCr)
Chest depth (ChD)
Width of the chest (WCh)
Width of the croup (WCr)
Width of the waist (WWa)
Girth circumference (GiC)
Cannon circumference (CaC)
Body length (BoL)

Each measurement was taken twice, and the average value was used for statistical analysis. Note that CaC was measured for the left forelimb.

3D image construction using multiple 3D scanners

A total of 4 smartphones capable of 3D scanning (iPhone 12 Pro, Apple Inc., Cupertino, CA, USA) were used to take the 3D images of each horse using a 3D image capture application (3D Scanner App 1.9.5, LAAN LABS, New York/Berlin/New Orleans).

Each horse stood without a rider and in the same position as used for manual measurements. The 3D scanning was performed by four people who simultaneously moved their devices up and down slowly and smoothly, as if tracing the horse's body, while maintaining a safe distance (1–2 m). Each measurer was responsible for scanning one of the following areas: left front (cannon circumference area and right shoulder end to left flank), left rear (left flank to right croup), right rear (left croup to right flank), and right front (right flank to left shoulder). CaC was measured only for the left forelimb as in the manual measurement. To facilitate the subsequent compositing process, each measurer scanned their own area of responsibility with a slight overlap. Since the horses often moved their head and neck, these areas were not included in the scanning. The time spent per scan was 15–20 sec. The time required for each animal, including checking of images and re-scanning, was approximately 15 min.

Captured 3D images were imported into 3D image analysis software (CloudCompare 2.10.2 Stereo, GNU General Public License), cropped, and combined. First, the ground and background in each 3D image were removed (cropping). The four cropped 3D images were combined into a left front and left rear image and a right front and right rear image. These two images were then combined into a left-right image. The 3D image analysis software is equipped with a compositing function which automatically combines the two images into a single image by specifying multiple points of common objects in the two images. The completed whole-body 3D image was then imported into another 3D image analysis software (Fusion 360, Autodesk, San Rafael, CA, USA), and body measurements were taken on the image. The measurement sites were the same as the manual measurement sites. Therefore, all measurements except CaC were taken using the combined images from four directions; CaC was measured using only images from the left front. Each body measurement on the 3D image was taken twice, and the average value was used for statistical analysis.

BW

The BW of each horse was measured on a weight scale. Estimated BWs from both manual and 3D measurements were determined using the following formula derived by Wagner and Tyler [17]:

$$\text{Estimated BW (kg)} = \text{girth circumference (cm)}^2 \times \text{body length (cm)}/11{,}880.$$

Statistical analysis

Data are presented as the mean ± standard error (SE). Statistical analyses were performed using statistical software (IBM SPSS Statistics version 21, IBM Corp., Armonk, NY, USA). The paired *t*-test and Pearson product-moment correlation coefficients were used to compare 3D measurements with manual measurements. Repeated measures one-way analysis of variance was used for comparisons among estimated BWs calculated from the 3D measurements, estimated BWs calculated from the manual measurements, and actual measured BWs. The coefficient of determination (R^2) and root-mean-square error (RMSE) between the manual and 3D measurement methods were calculated for all measurement data. Variations between the manual and 3D measurement data were determined using Bland–Altman plots [1]. Differences between data from both measurement methods were plotted against their means. The one-sample *t*-test was used to determine if the mean differences were significantly different. Differences were considered to be significant at $P<0.05$. According to the method of Pérez-Ruiz *et al.* [15], the relative error formula was used to compare manual measurements with 3D measurements to determine 3D measurement errors:

$$\text{Relative error (\%)} = (\text{3D Measurement} - \text{Manual Measurement})/(\text{Manual Measurement}).$$

Results

Figure 1 shows an example of a 3D composite image obtained in the present study. Lengths, widths, and circumferences of each body part determined by the two methods are noted in Table 1. There were no significant differences between the two methods for HBa, HCr, ChD, WCh, WCr, and WWa. HWi and BoL were significantly larger in manual measurements, while GiC and CaC were significantly larger in 3D measurements ($P<0.05$). The correlation coefficient between the manual and 3D measurement methods (r) was significant for all measurements except WCh (r=0.667, $P=0.050$) and CaC (r=0.540, $P=0.134$). The relative errors for WCh (3.25%) and CaC (7.05%) were also higher than for other measurements.

Figure 2 shows the results of the regression analysis between manual and 3D measurements. Simple regression analysis revealed a strong correlation (r=0.9997, $P<0.001$). The R^2 and RMSE were 0.9994 and 1.612, respectively.

Figure 3 shows Bland–Altman plots demonstrating the degree of agreement between manual and 3D measurements. The mean difference (3D-manual) was 0.25 cm, and it was not significantly different from 0 according to the one-sample *t*-test ($P=0.141$).

The BWs and estimated BWs calculated by the two

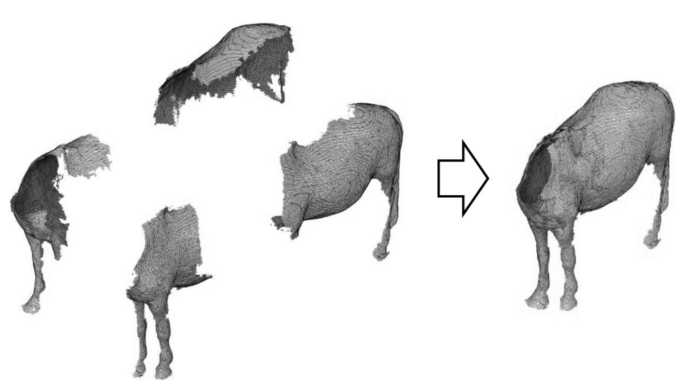

Fig. 1. 3D composite image obtained from four segmented images.

Table 1. Comparison of body measurements between the manual and 3D measurement methods

Measurement	Manual (cm)		3D (cm)		Paired *t*		Mean relative error	Correlation		
	Mean	SE	Mean	SE	*P*		(%)	r	*P*	
HWi	159.9	2.6	159.4	2.6	0.039	*	−0.28	0.998	0.000	**
HBa	150.8	2.6	150.8	2.5	0.981		0.00	0.996	0.000	**
HCr	159.2	2.6	159.0	2.5	0.417		−0.13	0.995	0.000	**
ChD	76.6	1.2	77.3	1.1	0.106		0.96	0.945	0.000	**
WCh	38.6	0.7	39.9	0.6	0.050		3.25	0.667	0.050	
WCr	50.6	0.5	49.6	0.8	0.080		−1.89	0.823	0.006	**
WWa	52.2	1.0	53.0	0.9	0.066		1.64	0.933	0.000	**
GiC	191.0	1.8	192.5	1.8	0.045	*	0.80	0.937	0.000	**
CaC	20.6	0.3	22.0	0.7	0.030	*	7.05	0.540	0.134	
BoL	175.6	2.8	174.0	2.8	0.021	*	−0.89	0.980	0.000	**

HWi, height at the withers; HBa, height at the back; HCr, height at the croup; ChD, chest depth; WCh, width of the chest; WCr, width of the croup; WWa, width of the waist; GiC, girth circumference; CaC, cannon circumference; BoL, body length. Relative error (%)=(3D Measurement − Manual Measurement)/ (Manual Measurement) × 100. *$P<0.05$; **$P<0.01$. SE, standard error; r, Pearson correlation coefficient.

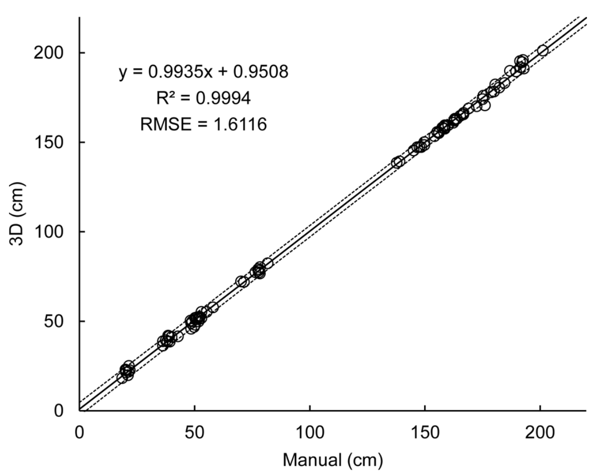

Fig. 2. Regression analysis comparing manual and 3D measurements. The dashed line reflects the 95% confidence interval. R^2, coefficient of determination; RMSE, root-mean-square error.

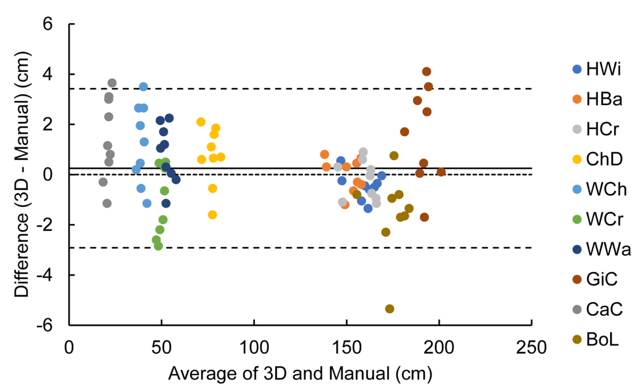

Fig. 3. Bland–Altman plots demonstrating the degree of agreement between manual and 3D measurements. The solid line is the mean difference, the upper dashed line represents the upper limit of agreement (difference + 1.96 × standard deviation (SD)), and the lower dashed line represents the lower limit of agreement (difference − 1.96 × SD).

methods are noted in Table 2. The values estimated by the two methods were generally consistent with the actual measured values. There were no significant differences between the estimated BWs calculated from the 3D measurements, estimated BWs calculated from the manual measurements, and the actual measured BWs (P=0.71).

Discussion

The accuracy of the method with the four devices developed in this study was evaluated by means of valuation indices indicating the degree of agreement with the results of manual measurements: correlation coefficients, relative errors, significant differences, and Bland-Altman plots. The correlation coefficients between the manual and 3D measurement methods were significant for all measurements except WCh and CaC. The correlation coefficients in the trunk were smaller for WCh, WCr and WWa, where calipers were used in manual measurements. Measurement using calipers is difficult, and this may have resulted in lower correlation coefficients. The absolute values of the relative errors for the WCh, WCr and WWa in the trunk also exceeded 1, and this was considered to have occurred for the same reason. CaC had the lowest correlation coefficient and the highest relative error. The left forelimb was scanned directly by one measurer to measure the CaC, and a stereo-

Table 2. Sex, age, breed, body weight, and estimated body weight of each horse

Horse No.	Sex	Age (years)	Breed	BW (kg)	Estimated BW	
					Manual (kg)	3D (kg)
#1	M	4	Crossbred[a]	502	506.9	516.1
#2	G	18	Thoroughbred	550	549.4	542.0
#3	G	13	Crossbred[b]	446	428.1	433.9
#4	G	19	Thoroughbred	594	628.4	624.4
#5	G	17	Thoroughbred	552	539.9	539.5
#6	M	16	Thoroughbred	572	540.6	538.5
#7	G	16	Thoroughbred	552	541.9	548.2
#8	G	8	Thoroughbred	546	561.5	576.6
#9	G	16	Thoroughbred	562	567.0	576.6
Mean	-	14.1	-	541.8	540.4	544.0
SE	-	1.7	-	14.5	17.8	17.3

G, gelding; M, mare; BW, body weight. [a]Mix × Haflinger. [b]Haflinger × Japanese native horse. Estimated BW [kg]=(girth circumference in cm)^2 × (body length in cm)/11,880 (Wagner and Tyler, 2011 [17]).

Table 3. Comparison of each valuation index between the previous report and this study

Measurement	Paired *t* test *P*-value		Absolute value of relative error (%)		Correlation coefficient		Outside 95% CI in Bland-Altman plots	
	Previous	This study	Previous	This study	Previous	This study	Previous	This study
HWi		<0.05						
HBa	<0.05							
HCr	<0.05		>1.0				√	
ChD								
WCh				>1.0		0.667 (ns)		√
WCr				>1.0				
WWa			>1.0	>1.0	0.153 (ns)		√	
GiC		<0.05					√	√
CaC	<0.05	<0.05	>1.0	>1.0	0.248 (ns)	0.540 (ns)	√	√
BoL		<0.05						√

Data from our previous report is cited [11]. ns, not significant; CI, confidence interval. For other definitions, see Table 1.

scopic image was constructed without combining it with other images. The main reason for the low CaC accuracy was the influence of hair. Additionally, the limitations of the devices used for scanning, which are unable to accurately construct 3D images of small or thin objects, were another reason for the low accuracy.

Significant differences between the two measurement methods were observed in 4 (HWi, GiC, CaC, and BoL) of the 10 body measurements. These differences were largely due to the influence of body hair or the difficulty in measuring the shortest possible distance during manual measurement. The Bland–Altman plots demonstrated that the manual measurements for HWi were greater than the 3D measurements in all but one horse. We speculate that measurements using a stick scale will be greater than the actual body height unless the measurer places it completely perpendicular to the ground. BoL is another measurement for which it is difficult to measure the shortest possible distance manually. For manual measurements, a tape measure is placed in contact with the horse's body, and the measurer slides a finger along it to determine the shortest possible length. Horses are sensitive to this and often move slightly. The 3D measurements for GiC and CaC were considered to be larger than the manual measurements because of the large effect of hair thickness.

It was very important to compare the accuracy in this study with that in our previous report [12]. Table 3 shows the body parts that showed poor values in each of the valuation indices: significant differences, absolute relative errors, correlation coefficients, and Brandt-Altman plots. The results showed that there were four measurements in this study (HWi, GiC, CaC, BoL) and three measurements in the previous study (HBa, HCr, CaC) for which the *p*-values of the paired *t*-test were below 0.05. There were also four measurements in this study (WCh, WCr, WWa, CaC) and three measurements in the previous study (HCr, WWa, CaC) for which the absolute values of the relative errors were larger than 1.0. There were two measurements with no significant correlation in both this study (WCh, CaC) and the previous study (WWa, CaC). There were four measurements that fell outside the 95% confidence interval in the Bland-Altman plots, both in this study (WCh, GiC, CaC, BoL) and the previous study (HCr, WWa, GiC, CaC). Therefore, based on the number of measurements showing discrepancies between the manual and 3D measurement methods, the current method was considered slightly inferior to the previous one.

However, it was necessary to consider the results not only based simply on the number of discrepancies but also in more detail based on the similarities and differences between the current and previous valuation indices. One similarity was that all four indicators for CaC showed poor values both in this study and the previous study. The reasons for this include the fact that the method used for CaC was the same in this study and the previous one, in addition to the influence of hair and the limitations of the scanners. A second similarity was that the absolute values of the relative error for WWa exceeded 1 in both the current and previous study. The difficulty of measuring WWa with calipers in manual measurements was a common cause of this. A third similarity was that GiC was outside the 95% CI for the Bland-Altman plots. A common cause of this was the influence of body hair.

On the other hand, one of the differences between the current and previous valuation indices was that the *P*-values were below 0.05 for HWi and BoL in this study. These significant differences were due to the fact that HWi and BoL are measurements for which it is virtually impossible to measure the shortest possible distance manually. Therefore, these discrepancies were considered to be similarities rather than differences, as significant differences in HBa and HCr were also produced by the same cause in the previous study. Another difference was that the relative error, correlation coefficient, and Bland-Altman plots for WCh showed poor values. This difference was also considered a similarity rather than a difference, as WCh was also measured using calipers.

Furthermore, the results of simple regression analyses of all body measurements in both studies were extremely similar (this study, $y=0.9938x + 0.429$, $R^2=0.9994$; previous study, $y=0.9935x + 0.9508$, $R^2=0.9994$). Based on these many similarities, the method using four devices was evaluated to be comparable to the method using one device in terms of accuracy and to be sufficiently applicable on-site.

Regarding the actual measurement situation, there were considerable differences between the method with four devices and that with one device. In our previous study with one device, one experimenter scanned the horse over the course of 1 min while walking slowly around the horse, starting from the front left of the horse and then moving to the right lateral view, caudal view, and left lateral view before returning to the front, moving the device up and down smoothly. In this study, however, scanning was completed in approximately one-quarter of that time. Simultaneous imaging using 4 scanners significantly reduced the imaging time. Not many horses can stand still for one min, but many can stand still for 15 sec. Completion of scanning in a short amount of time made it possible to perform non-contact body measurements even on incompletely trained horses that could not remain stationary for long periods of time. Furthermore, the 3D image capture application used in the present study captured the actual color of the object and produced a 3D image of it. This allowed the images to be easily combined without the need to mark the horse's body, enabling complete non-contact measurement.

One major problem in this study was that four persons were needed to take the measurements. This is a substantial problem on small farms. One means of overcoming this problem would be the development of an automatic measurement system equipped with multiple scanners. A similar system has been developed for cattle, and it was reported to be capable of measuring with an accuracy of up to 20 mm error [10]; however, the size and cost of the equipment are major hurdles. In the case of horses, nervous individuals often exhibit aversive reactions to large devices. On the other hand, handheld devices capable of performing 3D scans and the applications for them are improving day by day. Equipment that can scan more quickly will soon be developed. If one person could operate two scanners and two measurers performed measurements simultaneously, outputs similar to this study could be achieved by two measurers.

BW is also an important index for evaluating horses, as is body conformation. Especially for young or pregnant horses, regular measurement and recording of BW is extremely important. Weight scales are the most reliable method of measurement, but a scale is often not available at horse farms [3, 16]. According to the results of an online survey of horse owners, although more than half (60%) regularly monitored their horses' weights, only 5% actually used weight scales [13]. Estimation formulas are recommended when weight scale measurements are not possible [2, 11]. As adopted in the present study, formulas using GiC and BoL measurements are common [2, 6, 17]. However, since body conformation differs depending on breed and age, estimation formulas cannot be applied to all horses, and better estimation formulas are required. Some of the reported estimation formulas use measurement sites that would be difficult to measure manually, such as umbilical girth and length from the tuber ischii to elbow [9]. Using 3D measurements, BW can be estimated from the lengths of sites that are difficult to measure manually. Therefore, rapid measurement of many sites by 3D measurement can allow more accurate BW estimation equations to be constructed.

In conclusion, the correlation coefficients between the manual method and 3D measurement method using composite images were significant for eight of the 10 body measurements ($P<0.01$). There were no significant differences between the two measurement methods for six of the 10 body measurements. The relative errors varied from −1.89% to 7.05%. The accuracy of the developed 3D measurement method using four devices in this study was comparable to the accuracy of the previously published case with a single device. The most significant achievement in this study was the successful reduction of the scanning time. Scanning from four directions with four scanners dramatically reduced the measurement time. This allowed for the completion of measurements while the horse was standing still. The four segmented body images were easily combined on a computer to construct an image of the entire horse body without any problems. This research enabled non-contact horse body measurements that can be practically applied in the field.

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