Original Article

Accuracy and precision of a 3D anthropometric facial analysis with and without landmark labeling before image acquisition

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ABSTRACT

Objective: To determine the influence of landmark labeling on the accuracy and precision of an indirect facial anthropometric technique.

Materials and Methods: Eighteen standard linear craniofacial measurements were obtained from 10 adults using the 3dMDface system, with landmarks labeled (Labeled_3D) and without landmarks labeled (Unlabeled_3D) before image acquisition, and these were compared with direct anthropometry (Caliper). Images were acquired twice in two different sessions 1 week apart (T1 and T2). Accuracy and precision were determined by comparing mean measurement values and absolute differences between the three methods.

Results: Mean measurements derived from three-dimensional (3D) images and direct anthropologic measurements were mostly similar. However, statistically significant differences ($P < .01$) were noted for seven measurements in Labeled_3D and six measurements in Unlabeled_3D. The magnitudes of these differences were clinically insignificant (<2 mm). In terms of precision, results demonstrated good reproducibility for both methods, with a tendency toward more precise values in Labeled_3D, when compared with the other two techniques ($P < .05$). We found that Labeled_3D provided the most precise values, Unlabeled_3D produced less precise measurements, and Caliper was the least capable of generating precise values.

Conclusions: Overall, soft tissue facial measurement with the 3dMDface system demonstrated similar accuracy and precision with traditional anthropometry, regardless of landmarking before image acquisition. Larger disagreements were found regarding measurements involving ears and soft tissue landmarks without distinct edges. The 3dMDface system demonstrated a high level of precision, especially when facial landmarks were labeled. (*Angle Orthod.* 2011;81:245–252.)

KEY WORDS: Three-dimensional; Anthropometry; Soft tissue analysis

INTRODUCTION

Craniofacial anthropometry plays an important role in treatment planning, evaluation, and outcome assessment in several health disciplines, especially in orthodontics.[1–5] Traditionally, the primary sources of craniofacial measurement have been direct anthropometry, two-dimensional (2D) photography, and cephalometry.[2,5] Recently, three-dimensional (3D) technologies such as laser scanning, helicoidal and/or cone-beam computerized tomography, and 3D stereophotogrammetry have been systematically utilized for anthropometric assessment instead of the traditional direct caliper-based measurement.[6–14]

Although the direct anthropometric technique is noninvasive, displays technological simplicity, and is a low-cost approach, it is time consuming, requires adequate training of the examiner and proper instrumentation, and depends on patient cooperation for reliable results; as a result, this method may be impractical in the clinical setting.[14–16] Moreover, the direct technique does not provide a permanent record other than a list of numbers at the end of data collection. Hence, technological advances in this area have

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focused primarily on developing noninvasive devices and more efficient anthropometric indirect techniques to allow their use in the daily clinical routine.[9,11]

Stereophotogrammetry, a three-dimensional technique used to capture topographic surface data, has been used for craniofacial imaging for over 50 years. More efficient systems have been developed recently, such as the 3dMDface system (3dMD LLC, Atlanta, Ga), which was designed specifically for imaging the human face in three dimensions. 3dMDface is a surface imaging system that acquires a 180° image of a person's face from ear to ear in only 1.5 milliseconds. Furthermore, the 3dMDface is capable of linear, angular, and volumetric measurements of 3D surfaces.[6,11,17–19] Its rapid image acquisition reduces artifacts caused by movement during the acquisition process. However, as with all measuring techniques, inherent sources of error may affect the accuracy and precision of the facial analysis.[14,16,20,21]

Previous studies have examined the reliability of certain 3D stereophotogrammetric systems for soft tissue facial measurements.[6–8,14,17–19,22,23] However, only four previous studies examined the precision of the facial measures acquired from the 3dMDface images.[6,17–19] Two studies focused on the precision and reliability of landmark placement on 3dMD images by comparing the x,y,z coordinates of each landmark,[6,19] and only two[17,18] compared the 3dMD system against direct anthropometry; one study was performed in vivo.[18] In only two studies were the landmarks labeled before image acquisition and/or direct measurements.[17,18]

Using a valid and reliable indirect morphometric system is a primordial requisite in the selection of a device and method. However, time-consuming methods and complex systems can alter an efficient clinical operation, making their routine use impractical. For instance, labeling the landmarks before direct anthropometric measurement has been a common practice.[7,17,21,23] Despite the fact that in several studies landmark labeling was done before image acquisition, the value of this procedure in increasing the accuracy and precision of facial morphometric analysis using photogrammetric methods is not completely understood.[14] Therefore, it was considered important to determine whether prior labeling is a necessary procedure when the 3dMD system is used for morphometric purposes.

In this study, the precision and accuracy associated with indirect anthropometry were investigated using the 3dMDface system by comparing it with direct anthropometry. We specifically evaluated whether a systematic difference exists between linear measurements obtained from caliper measurements and those obtained using the 3dMDface system with and without prior labeling of facial landmarks.

MATERIALS AND METHODS

Ethics approval was obtained for this study from the Institutional Review Board of the University of Minnesota. The study sample comprised 10 healthy adults (8 males, 2 females; mean age, 32.96 $\pm$ 5.32 years) with no history of craniofacial dysmorphology or facial surgery.

Eighteen facial measurements were derived from 19 anthropometric soft tissue landmarks from each subject (Figure 1 and Table 1).[14,16]

Facial measurements, obtained with both direct caliper-based and indirect 3D stereophotogrammetry-based anthropometric analysis, were taken twice for each subject, in sessions conducted 1 week apart (T1 and T2) to reduce the potential for memory bias. Each subject's session comprised three consecutive and distinct procedures: (1) 3D photograph acquisition without landmarks (Unlabeled_3D), (2) direct caliper-based assessment with labeled landmarks (Caliper), and (3) 3D photograph acquisition with labeled landmarks (Labeled_3D).

Three-dimensional facial images were obtained using the 3dMDface system under standard clinical lighting conditions. The system was calibrated at the beginning of each session in keeping with the manufacturer's protocol (Figure 2).

Acquisition of 3D Photographs Without Landmarks Labeled

Each subject's Unlabeled_3D images were obtained with the subject seated on a chair facing the center of the 3dMD device in a natural head position and with neutral facial expression. Subjects were instructed to wear a headband to remove hair strands from their face and ears when needed. Each image was captured within 1.5 milliseconds and was reviewed immediately after it was obtained using the 3dMDface software to ensure absence of acquisition errors such as imaging artifacts, blurring, absence of surface data, or lack of neutral facial expression. Images with the wrong characteristics were deleted, and new images were obtained to ensure that they fit the set criteria.

Caliper Measurement With Landmarks Labeled

Immediately after the Unlabeled_3D photograph was obtained, all landmarks, except for endocanthion, exocanthion, and stomion, were labeled on each subject's face using a surgical marking pen. Then, linear measurements were taken directly with a digital caliper on the subjects' labeled faces, one after the other, according to the Farkas method.[16] Special attention was given to use of minimal pressure to avoid soft tissue deformation by the caliper during measurements.

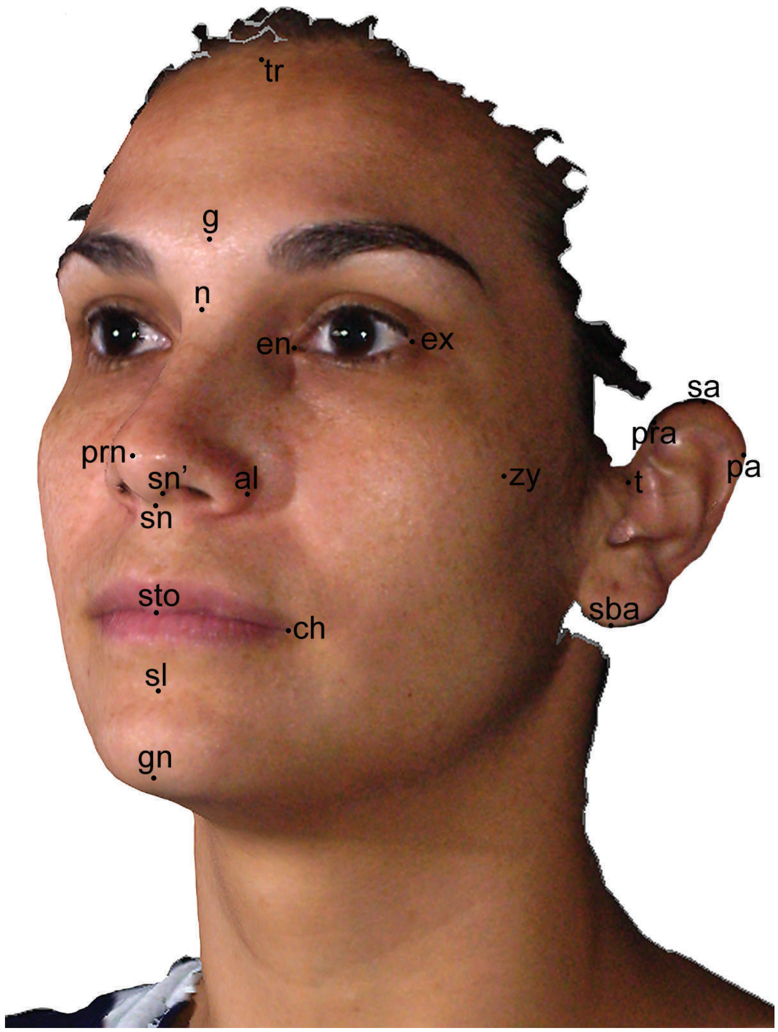

Figure 1. Three-dimensional photograph obtained with the 3dMDface system showing soft tissue landmarks used for direct and indirect facial measurements.

Acquisition of 3D Photographs With Landmarks Labeled

After the direct measurements were finished, a second 3D facial image with facial landmarks labeled was acquired using the method described previously. Acceptable images were saved as permanent files.

All procedures, including landmark labeling, image acquisition, direct facial measurement, and image analysis, were performed twice by the same operator. During analysis of 3D facial images, landmarks were identified on each 3D surface, whether they were labeled or not, using the 3dMDface software. Frontal, lateral, and submentovertex views were used to identify medial and bilateral landmarks. Linear measurements between landmarks were calculated using the caliper function of the software and were recorded in millimeters.

Accuracy and Precision Testing of the 3dMDface System

A paired Student's *t*-test was used to compare the accuracy and precision of direct and indirect measurement techniques. Accuracy of the labeling methods was determined by comparing the average differences of linear measurements obtained from Unlabeled_3D and Labeled_3D vs those obtained from Caliper. Differences were considered significant at $P < .01$. Absolute differences between T1 and T2 were compared to evaluate the precision of each method. Differences were considered significant at $P < .05$. To determine whether any of the measurement methods tended to give systematically different values, average differences (AVE-DIFF) comparing T1 and T2 measures were also calculated and tested. Differences greater than 2 mm in any of the measurements were considered clinically significant.

Table 1. Anthropometric Measurements and Landmarks[16]

Linear Measurements	Landmarks
Skull-base width	tragion-tragion (t-t)
Forehead height	trachion-glabella (tr-g)
Face height	nasion-gnathion (n-gn)[a]
Upper face height	nasion-stomion (n-sto)
Lower face height	subnasale-gnathion (sn-gn)
Face width	zygion-zygion (zy-zy)
Intercanthal width	endocanthion-endocanthion (en-en)
Right eye fissure width	endocanthion-exocanthion (en-ex)
Biocular width	exocanthion-exocanthion (ex-ex)
Nose height	nasion-subnasale (n-sn)
Nose width	alare-alare (al-al)
Nasal tip protrusion	subnasale-pronasale (sn-prn)
Columella width	subnasale′-subnasale′ (sn′-sn′)[b]
Mouth width	cheilion-cheilion (ch-ch)
Upper lip height	subnasale-stomion (sn-sto)
Lower lip height	stomion-sublabiale (sto-sl)
Right ear width	preaurale-postaurale (pra-pa)
Right ear height	superaurale-subaurale (sa-sba)

[a] Soft tissue analog of bony landmark gnathion.

[b] Midpoint of the columella crest, where the thickness of the columella is measured.

RESULTS

Accuracy

Results of the accuracy of Labeled_3D and Unlabeled_3D relative to Caliper are presented in Table 2. Statistically significant differences were noted for seven Labeled_3D measurements and six Unlabeled_3D measurements; three were horizontal (skull-base width, face width, intercanthal width), and five were vertical measurements (two found in both Labeled_3D and Unlabeled_3D: upper face height, upper lip height; two found only in Labeled_3D: lower lip height and right ear height; and one found only in Unlabeled_3D: lower face height). However, of the 18 measurements taken, only skull-base width, face width, intercanthal width, and right ear height showed a mean difference larger than 2 mm.

Compared with direct anthropometry, mean measurement values derived from the 3dMDface system (Labeled_3D and Unlabeled_3D) tended to be larger, thus giving negative average differences (Table 2). Overall, 11 of 18 measurements for Labeled_3D and 12 of 18 measurements for Unlabeled_3D had mean values larger than those derived from Caliper. However, besides skull-base width and face width (AVG_DIFF $>$7 mm), AVG_DIFF values between the two 3D methods and Caliper were not clinically significant (mean: -0.96 ± 0.62 for unlabeled-3D, and -0.93 ± 0.75 for Labeled_3D).

Precision

The precision tests between measurements obtained at T1 and T2 using the three different methods are shown in Table 3. Overall, the three methods showed no systematic differences between T1 and T2 measurements. Of 54 tests, only one measurement—right ear height (AVG_DIFF $= -0.55$ mm)—was

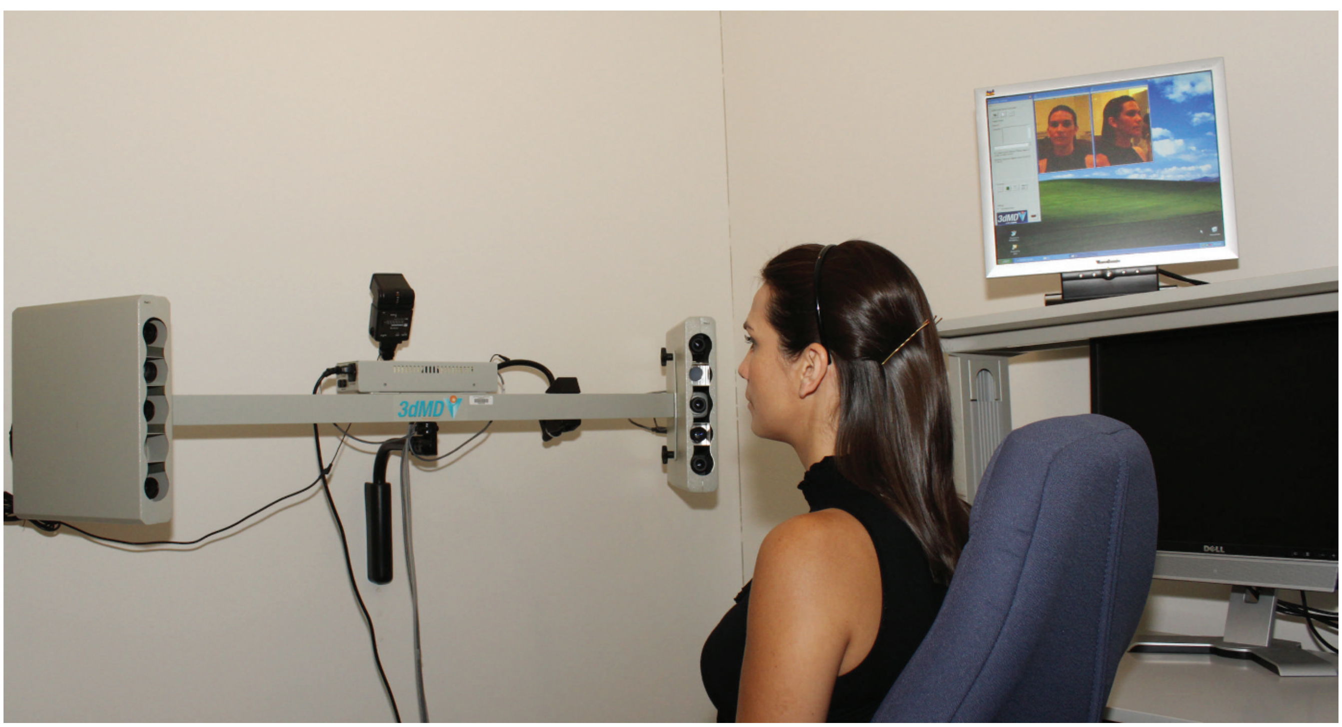

Figure 2. Imaging acquisition with the 3dMDface system.

Table 2. Average Differences Between Caliper and 3dMD Without and With Landmarks Labeled[a]

Measurements	Caliper-Unlabeled_3D AVE-DIFF	SE	P Value*	Caliper-Labeled_3D AVE-DIFF	SE	P Value*
Skull-base width	**−9.81**	**0.59**	**.000**	**−9.40**	**0.57**	**.000**
Forehead height	1.16	1.02	.286	1.60	0.64	.035
Face height	−0.79	0.69	.283	−0.28	0.55	.618
Upper face height	**−1.55**	**0.41**	**.004**	**−1.94**	**0.32**	**.000**
Lower face height	**−1.31**	**0.32**	**.003**	−0.35	0.33	.313
Face width	**−7.40**	**0.86**	**.000**	**−7.44**	**0.56**	**.000**
Intercanthal width	**−1.90**	**0.36**	**.001**	**−2.13**	**0.28**	**.000**
Right eye fissure width	1.06	0.40	.027	1.04	0.36	.018
Biocular width	0.72	0.76	.374	0.78	0.75	.322
Nose height	−0.29	0.23	.245	−0.74	0.24	.014
Nose width	−0.02	0.27	.956	0.57	0.38	.166
Nasal tip protrusion	0.66	0.44	.169	0.10	0.31	.751
Columella width	−0.88	0.30	.021	−0.47	0.15	.011
Mouth width	0.85	0.68	.248	0.15	0.68	.836
Upper lip height	**−1.39**	**0.19**	**.000**	**−1.19**	**0.32**	**.005**
Lower lip height	−1.20	0.61	.082	**−1.24**	**0.30**	**.003**
Right ear width	−0.29	0.89	.752	−0.01	0.81	.995
Right ear height	1.01	0.84	.263	**2.58**	**0.57**	**.002**

[a] AVE-DIFF indicates average differences (mm); SE, standard errors.

* Significance: $P < .01$.

statistically significant ($P < .05$) when assessed by the Labeled_3D method. The average difference between T1 and T2 for all measurements was lower than 0.5 mm, except for right ear width (−0.53 mm) in the Caliper method and right ear height in the Caliper (−1.12 mm) and Labeled_3D methods (−0.55 mm).

Paired Student's *t*-tests showed a tendency toward more precise values (AVG_DIFF), although not significant, for Labeled_3D, followed by Unlabeled_3D; Caliper was the least precise method (Tables 3 and 4). This pattern of precision is best illustrated in Figures 3A and 3B; these boxplots show the distribution of the difference between the three methods and two facial features, skull-base width (t-t) and face height (n-gn), respectively.

Given that no systematic trend was observed from T1 to T2 for any of the methods, we compared their respective precision by taking the absolute value of the difference (ABS_DIFF) between T1 and T2 (ie, stripping off any minus signs) and compared the methods according to the ABS_DIFF (Table 4). When the ABS_DIFF of the measurements obtained by Caliper was compared with Labeled_3D and Unlabeled_3D, Caliper measurements tended to have a larger ABS_DIFF; eight were statistically significantly larger in the Unlabeled_3D method. When absolute differences between the two 3D methods were compared, Unlabeled_3D showed a larger ABS_DIFF than Labeled_3D in 14 of 18 measurements; however, only four were significantly different.

DISCUSSION

Accuracy

In the current study, good agreement was observed between measurements derived through Unlabeled_3D and Labeled_3D methods and those obtained via direct anthropometry. Although statistically

Table 3. Average Differences (T1-T2) for 3dMD With Nonlabeled Landmarks, With Caliper, and With Landmarks Labeled Methods[a]

Measurements	Unlabeled_3D AVE-DIFF	SE	P Value*	Caliper AVE-DIFF	SE	P Value*	Labeled_3D AVE-DIFF	SE	P Value*
Skull-base width	0.2	0.26	.468	−0.09	0.89	.920	0.06	0.10	.572
Forehead height	−0.15	0.19	.442	−0.15	0.28	.611	−0.02	0.08	.852
Face height	−0.16	0.19	.410	0.43	0.97	.669	−0.02	0.08	.782
Upper face height	0	0.22	1.000	−0.32	0.21	.166	0.12	0.14	.402
Lower face height	0.49	0.32	.159	−0.02	0.37	.958	−0.02	0.12	.876
Face width	−0.34	0.47	.485	−0.24	0.41	.569	−0.11	0.09	.276
Intercanthal width	0.12	0.24	.624	−0.15	0.27	.595	−0.2	0.17	.263
Right eye fissure width	−0.07	0.21	.748	0.2	0.25	.438	0.01	0.22	.971
Biocular width	−0.05	0.27	.859	0.46	0.59	.459	0.14	0.21	.519
Nose height	−0.31	0.29	.305	−0.05	0.22	.823	−0.01	0.11	.927
Nose width	−0.14	0.11	.218	0.17	0.21	.446	−0.02	0.09	.820
Nasal tip protrusion	0.16	0.22	.490	−0.52	0.41	.237	−0.14	0.08	.122
Columella width	0.08	0.12	.559	−0.14	0.19	.474	−0.14	0.09	.138
Mouth width	−0.17	0.09	.101	−0.16	0.37	.677	0.07	0.14	.634
Upper lip height	0.35	0.30	.271	0.23	0.25	.379	−0.05	0.12	.696
Lower lip height	0.12	0.14	.425	0	0.19	1.000	−0.09	0.08	.271
Right ear width	−0.35	0.24	.175	−0.53	0.36	.173	−0.06	0.17	.734
Right ear height	0.21	0.22	.358	−1.12	1.07	.324	**−0.55**	**0.20**	**.021**

[a] AVE-DIFF indicates average differences (mm); SE, standard errors.

* Significance: $P < .05$.

Table 4. Comparisons of Absolute Differences (T1-T2) Between the Three Different Methods[a]

	Caliper-Labeled_3D			Caliper-Unlabeled_3D			Labeled_3D/Unlabeled_3D		
Measurements	ABS-DIFF	SE	*P* Value*	ABS-DIFF	SE	*P* Value*	ABS-DIFF	SE	*P* Value*
Skull-base width	**1.79**	**0.60**	**.015**	1.29	0.67	.086	**−0.5**	**0.15**	**.010**
Forehead height	**0.57**	**0.14**	**.003**	0.34	0.21	.144	−0.2	0.14	.119
Face height	**1.94**	**0.77**	**.036**	1.59	0.72	.055	**−0.2**	**0.08**	**.036**
Upper face height	0.20	0.20	.353	0.14	0.22	.534	−0.1	0.16	.715
Lower face height	**0.56**	**0.21**	**.026**	0.05	0.40	.903	−0.5	0.24	.062
Face width	**0.71**	**0.25**	**.019**	−0.22	0.42	.612	**−0.9**	**0.30**	**.013**
Intercanthal width	0.35	0.25	.199	0.03	0.19	.895	−0.3	0.24	.211
Right eye fissure width	0.09	0.24	.723	0.09	0.19	.645	0.0	0.22	.993
Biocular width	0.54	0.50	.311	0.39	0.56	.502	−0.2	0.17	.392
Nose height	0.32	0.16	.074	−0.16	0.19	.424	−0.5	0.21	.050
Nose width	**0.35**	**0.14**	**.039**	0.25	0.12	.064	−0.1	0.08	.244
Nasal tip protrusion	**0.80**	**0.28**	**.020**	0.42	0.30	.191	**−0.4**	**0.13**	**.018**
Columella width	**0.24**	**0.10**	**.046**	0.24	0.11	.058	0.0	0.09	1.000
Mouth width	0.51	0.27	.095	0.57	0.24	.043	0.1	0.12	.619
Upper lip height	0.34	0.15	.052	0.00	0.24	1.000	−0.3	0.27	.246
Lower lip height	0.25	0.13	.089	0.10	0.17	.562	−0.2	0.09	.115
Right ear width	0.33	0.37	.400	0.10	0.37	.792	−0.2	0.16	.172
Right ear height	1.05	0.96	.302	1.35	1.01	.213	0.3	0.18	.123

[a] ABS-DIFF indicates absolute difference (mm); SE, standard errors.
* Significance: $P < .05$.

significant differences were noted for seven measurements with Labeled_3D and six measurements with Unlabeled_3D, the magnitude of these differences was mostly less than 2 mm. In nearly half of the measurements, mean differences were at the submillimeter level.

Of the measurements in which significant mean differences were observed, common factors appeared to unite them. Two measurements used landmarks from the ear, two used bony landmarks, and three used the landmark stomion. As previously demonstrated, locating landmarks on the ear is difficult because of the obscurity of the image, which is attributed to the subject's hair casting a shadow on the ear.[6] Furthermore, in this study, we used the 3dMDface system, which captures 180° of digital information, limiting extension of the facial surface acquired. For studies that require evaluation of the ear, the 3dMDcranial (3dMD LLC, Atlanta, Ga) may be a more appropriate system to use because it has a 360° full-head capture, which may improve the placement of landmarks on the ears.

Inaccuracies using 3dMD were also demonstrated in measurements using bony landmarks, such as zygion and gnathion. Bony landmarks require physical palpation for proper identification, which is not possible in indirect measurements and should be used with caution. A combination of direct identification and labeling of difficult landmarks may provide more accurate measurements than the use of indirect methods.[6,16,18]

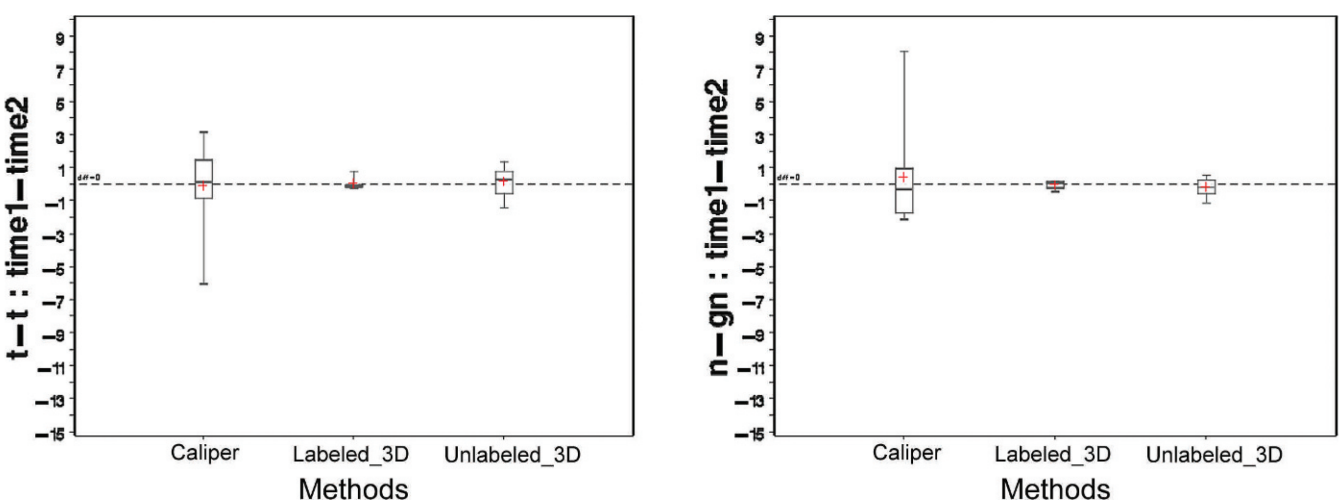

Figure 3. (A and B) Distribution of the difference between 3dMD measurements and Caliper measurements for skull-base width and face height.

Although all subjects were instructed to maintain a neutral facial expression with the lips at rest, it is possible that changes in facial expression contributed to changes in the position of some of the landmarks during image acquisition with 3dMD. Variation in landmarks that crossed the labial fissure (ie, stomion) or in those located in the mandible or lips has been previously observed by other authors who used 3D systems.[6,14] They attributed these errors to alterations in the position of those structures caused by changes in facial expression, breathing, or speaking. On the other hand, significant differences in the measurement of intercanthal width (en-en) between Caliper and 3D images could be due to error in Caliper measurement, because this is typically a small measurement that is not marked before Caliper measurement, and it is an uncomfortable measurement for subjects. These limitations do not occur when indirect measurement is used; thus we speculate that the inaccuracy was due to an error in Caliper measurement and was not associated with the 3dMDface system.

Previous comparisons between the accuracy of direct anthropometry and various 3D indirect methods, including laser scanning and stereophotogrammetry, have shown mixed results. Whereas some reported a high degree of correlation between direct and indirect methods, others reported significant differences among them.[14] Our accuracy results were most comparable with those of Weinberg et al.[17] and Wong et al.,[18] suggesting that the accuracy of the 3dMD system is at least as good as that of other 3D technologies currently used, such as direct anthropometry.

Compared with direct anthropometry, mean measurement values derived from the 3dMD system were typically larger. This tendency toward overestimation was observed in 11 of 18 measurements (including six of the seven significant) for Labeled_3D, and in 12 of 18 measurements (including all six significant) for Unlabeled_3D; however, these overestimations were mostly clinically insignificant.

Direct anthropometry, by definition, requires physical contact with the soft tissue of the face, whereas indirect anthropometry does not; these soft tissue structures are pliable and may be easily distorted during direct measurements. Nevertheless, previous studies have shown inconsistent data on this issue.[14]

Precision

When the data obtained from T1 to T2 were compared, all three methods showed no systematic differences between measurements at different times. For all 18 measurements obtained via the 3dMDface system, the mean difference between T1 and T2 was submillimeter. When techniques were compared, measurements derived from the 3dMDface had higher precision than those derived from Caliper, although this was not statistically or clinically significant. Furthermore, when Unlabeled_3D and Labeled_3D methods were compared, higher precision was observed with the former method.

Although differences in degrees of precision were observed among landmarks, no specific pattern was observed in this study. Previous studies have suggested that the magnitude of error in landmark precision tends to be greater in measurements of greater size, measurements using landmarks that are difficult to see, and measurements crossing the labial fissure.[6,14,24]

Because the current precision evaluation was not based on landmark coordinates (x,y,z), it is difficult to directly compare our data with those of previous 3dMD studies regarding precision of facial measurements.[6,19,22] The goal of our study was not to examine landmark localization per se, but to compare the precision of data obtained through the 3dMDface system with and without prior landmark labeling vs data obtained via traditional direct anthropometry. Our results indicate higher precision in the localization of landmarks with use of the 3dMDface system, regardless of landmark labeling before image acquisition.

Finally, 3D technologies for facial analysis offer the clinician a rapid means of soft tissue assessment and may improve orthodontic treatment planning and treatment outcomes assessment. Elimination of unnecessary steps and additional labeling of all facial landmarks before 3D image acquisition will result in a more efficient method of facial analysis. However, landmarks with well-defined borders or edges should be selected over landmarks that are placed on curved slopes and are not clearly defined, and landmarks that require palpation for identification should be directly identified and labeled before image acquisition to increase the accuracy and reproducibility of the measurements.

CONCLUSIONS

- Overall, soft tissue facial measurement with the 3dMDface system, regardless of landmark labeling, demonstrated good agreement with traditional anthropometry.
- Differences were observed in measurements involving ears and soft tissue landmarks without distinct edges. All three methods showed no systematic difference between T1 and T2 measurements.
- The 3dMDface system demonstrated a higher level of precision, especially when facial landmarks were labeled.

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