Accuracy and precision of a photographic system for the three-dimensional study of facial morphology

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ABSTARCT

Background: Facial analysis is vital for orthodontic treatment planning but traditional methods of facial analysis are incapable of fully capturing the three-dimensional complexity of the human face. The purpose of this study was to determine the precision and accuracy of facial anthropometric measurements obtained through low-cost digital three-dimensional photogrammetry system.

Materials and methods: Eighteen standard craniofacial measurements were obtained from faces of thirty young adults using two methods: calipers and 3D photos (obtained with a Photomodeler system). After marking anthropometric landmarks on the faces of the sample, direct measurements were taken using calipers then five photographs were taken at different angles and 3D model constructed and the same measurement were taken using Photomodeler. Differences between two methods were calculated. To test the precision of the new photogrammetric system, measurements were repeated on the same photographs by the researcher and then by another examiner and also a new set of photographs were taken for each individual and measurements were done on them. Three different precision estimates were calculated to measure random error for the new method.

Results: Systematic errors between the two methods were found for seven measurements but most mean differences were clinically insignificant (below 2 mm). In terms of measurement precision, no systematic biases were found between repeated measurements on the same photographs or on different photographs and our precision estimates showed a clinically acceptable level of repeatability for the Photomodeler system.

Conclusion: It can be concluded that Photomodeler 3D photogrammetry system can provide accurate and reliable facial measurements. It is relatively fast and requires only inexpensive equipment.

Key words: Three-dimensional; Anthropometry; Soft tissue analysis. (J Bagh Coll Dentistry 2012;24(1):138-145).

INTRODUCTION

Facial esthetics is an important personal and social concern. Attractive faces are judged to possess more socially desirable personality traits [(1)], and favorable facial esthetics are related to psychosocial well-being by children, young adults and parents [(2,3)]. So it is not surprising that current concepts in diagnosis and treatment planning focus on the balance and harmony of various facial features [(4)].

Traditionally, direct anthropometry, two-dimensional photogrammetry and cephalometry have served as primary methods for craniofacial measurement, but there is increasing awareness that these techniques are incapable of fully capturing the three-dimensional (3D) complexity of the human face [(5, 6)].Moreover, direct anthropometry can be time consuming in a clinical setting, whereas traditional 2D photogrammetry has been shown to be highly inaccurate [(7)] and cephalometry exposes subjects to radiation. Thus, each of these established techniques of data acquisition is suboptimal.

To address limitations of the 2D imaging systems, several types of 3D imaging have emerged, including computer-assisted tomography [(8)] and laser scanning [(9, 10)] and stereophotogrammetry.

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These methods are noninvasive, allow images to be archived, and avoid measurement errors that occur with 2D representations of 3D surfaces. The most promising method of soft tissue evaluation is stereophotogrammetry [(11)]. This method typically consists of a group of cameras with a fast capture time; the cameras capture different images of the subject from multiple angles simultaneously or rapidly, and dedicated software reconstructs a digital 3D image. A quick image acquisition reduces the effect of subject movements; in addition, there is no need for direct contact with the facial surface, thereby avoiding modification of soft tissues, which may cause errors in direct measurements [(12, 13)]. The major disadvantage of these new techniques is their cost, impeding their routine clinical use. Additionally, they often need dedicated spaces, which cannot be organized within dental and orthodontic offices, thus limiting the use of 3D analysis to university laboratories and research centers [(14)].

Accuracy and precision of any method are fundamental for a reliable analysis of craniofacial deformities [(15,16)]. So in this study the aim was to test the accuracy and precision of an innovative low-costsystem in measuring the facial soft tissues of healthy subjects. This system does not require a special space arrangement and uses an ordinary digital camera with commercially available software.

MATERIALS AND METHODS

The sample of this study composed of 30 adult subjects (20 males and 10 females) with an age ranged between 18-30 years. All subjects had no history of obvious craniofacial dysmorphology or facial surgery.

Eighteen linear facial measurements were derived from 20 anthropometric soft tissue landmarks from each subject [17] (Figure 1 and Table 1).

Facial measurements were taken with both direct caliper-based and indirect 3D stereophotogrammetry based anthropometric analysis. We assessed the accuracy of Photomodeler system by comparing these 18 facial linear measurements obtained from the latter with the same values obtained from direct facial measurements. Regarding precision, we divided the precision of Photomodeler into two components and test each one individually [14]. For testing the precision of tracing procedure, after at least 1 month, we repeated the measurements for all subjects using the same set of photographs and compared the results with those obtained from the first tracing. To determine the effect of repositioning on the precision of the system, another set of photographs has been taken for all subjects, also after one month, and the results obtained from those new photographs using Photomodeler software were compared with results obtained from the first set of photographs.

Direct Measurement

Before taking direct measurements all landmarks were marked on the faces of our sample using black liquid eyeliner except for Endocanthion (En), Exocanthion (Ex) and Stomion (Sto) because of their invasiveness. During landmarking, the subjects sat in a relaxed position, with natural head position. The subjects were also instructed to keep their teeth in light occlusion and their lips relaxed. Special attention was given to use of minimal pressure to avoid soft tissue deformation by the caliper during measurements. All linear measurments were taken using sliding caliper except for (T – T), (Zy – Zy) and (Go – Go) which were taken using spreading calipers.

Measurements using Photomodeler

After direct measurements we proceeded to take the photographs needed to construct 3D model using Photomodeler V. 6. The subjects sat in the same relaxed position, with natural head position.

We used a DSLR Canon camera (Rebel T3i) with a resolution of 18 MP and a 35 mm Canon lens. Calibration procedure was done for the camera as instructed by the developer of Photomodeler (EOS Systems Inc)[18]. Then the camera was attached to height adjustable tripod and five photographs were taken. One frontal , two at 60° to the right and left and two at 30° to the right and left. The distance from subjects was fixed at 1.5 meter (Figure 2) and (Figure 3). The subjects were instructed to remain still during taking the photographs and the whole procedure did not last more than 60 seconds. If there was any sign of subject movement during photographing we would repeat the whole procedure.Landmarking and Photographing were repeated on all subjects after at least one month to eliminate memory bias.

The photographs then were uploaded to a personal computer and were used to construct 3D model using Photomodeler software. After constructing the 3D model measurements were taken.

Statistical analysis

To determine the accuracy of the Photomodeler system, mean measurements derived from 3D photos were compared to mean measurements derived from calipers using paired student t-test. We considered a P value of .05 or smaller to be significant.

To test the precision of Photomodeler system - both for the tracing procedure and after repositioning- we used paired student T-test to assess any systematic error. While for random error three different precision estimates have been used: mean absolute difference (MAD), relative error magnitude (REM), and technical error of measurement (TEM).

MAD is a commonly reported precision estimate [19, 20]. Advantages of MAD include its simplicity to calculate, its easy interpretation for comparative purposes (it is in the original units of measurement), its lack of dependence on the size of the measurement, and the fact that it requires few assumptions about the data [20]. When dealing with only two observations, MAD is simple enough to calculate; for any particular measurement, average the absolute difference between the values at time 1 and time 2 across all subjects in the sample. The formula for calculating MAD is:

$$MAD = \Sigma \mid D \mid / N$$

Where D is the difference between the first and second measurement for every subject and N represents the number of individuals measured.

The second precision estimate, REM, was obtained by dividing the MAD for a given variable by the grand mean for that variable and multiplying the result by 100. In this form, the REM represents an estimate of error magnitude relative to the size of the measurement, expressed as a percentage. In terms of reliability, smaller percentages represent more precise measurements. The REM is important because error magnitude scores, by themselves, can be misleading. For example, the implications of a MAD score of 2 mm for a mean measurement value of 180 mm are quite different from those of a 2-mm MAD score for a mean measurement value of 18 mm; the former is 1% of the mean value, whereas the latter is 11%. For the purposes of this study, and following Weinberg et al. [21]REM scores were divided into five precision categories: scores less than 1% were deemed ‘‘excellent,’’ scores ranging from 1% to 3.9% were deemed ‘‘very good,’’ scores ranging from 4% to 6.9% were deemed ‘‘good,’’ scores ranging from 7% to 9.9% were deemed ‘‘moderate,’’ and scores exceeding 10% were deemed ‘‘poor.’’

Another additional precision estimates were included in this study: TEM. TEM (also called the ‘‘method error statistic’’) is one of the most widely used estimates of precision [22-24]. TEM ‘‘provides a standard deviation-like measure of the magnitude of error, and it is in the original units of measurement.’’ [24]. It can be used to generate both intra- and interobserver precision estimates. The formula for TEM when two measurements are involved is:

$$TEM = \sqrt{\Sigma D^2 / 2N}$$

where D represents the difference between the first and second measurement and N represents the number of individuals measured. Similar to MAD, smaller TEM values represent more precise measurements.

RESULTS

Accuracy of Photomodeler

Table 2shows that Among 18 linear measurements, 7 measurements obtained from Photomodeler were significantly different from the same measurements taken by caliper. However, mean differences were generally below 2mm except for skull base width (T-T) and bigonial width (Go-Go). Actually 8 of 18 distances showed a mean difference below 1 mm. 14 of the 18 means obtained by Photomodeler were larger than those obtained by caliper.

Precision of Photomodeler

Table 3 shows the means differences and precision estimates for the first and second measurements performed on the same photographs using Photomodeler after one month. The table shows that the mean difference for all variables to be less 0.5 mm. It also shows results of paired sample t–test which indicated that there are no significant difference between the means of any variable derived from these two sessions and thus no systematic error in the process of retracing in Photomodeler. All MAD values were at the submillimetric level except for (T-T) and (Ex-Ex). TEM values did not exceed one millimeter except with (Ex-Ex). Regarding REM values, all distances showed very good reproducibility except upper and lower lip vermilions (Ls-Sto) and (Sto-Li) which showed good reproducibility (REM = 5%).

Table 4 shows that there was no significant difference between the means of any variablederived from two different set photographs taken for the same subject after one month. It also shows the same three precision estimates that have been used previously. 7 variables has demonstrated High MAD (above 2mm) and high TEM (above 1.6mm) values those are skull base width (T-T), face width (Zy-Zy), bigonial width (Go-Go), intercanthal width (En-En), right eye width (En-Ex), biocular width (Ex-Ex) and right ear height(Sa – Sba). According to REM values, ten variable had very good reproducibility from 1- 4%, four had good reproducibility from 4-7% and four had moderate reproducibility and those were , (En-En), (En-Ex), (Ls-Sto) and (Sto-Li). No variable in our study had excellent (below1%) or poor (above 9%) reproducibility.

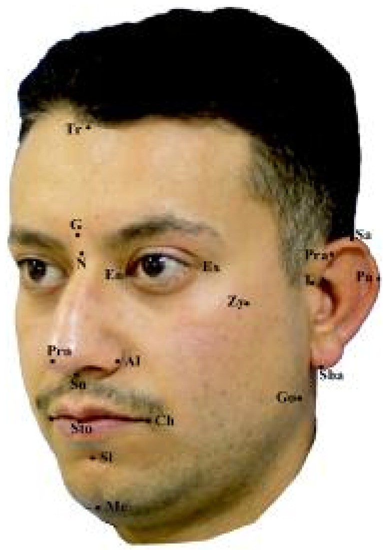

Figure 1: Facial anthropometric landmarks used in our study.

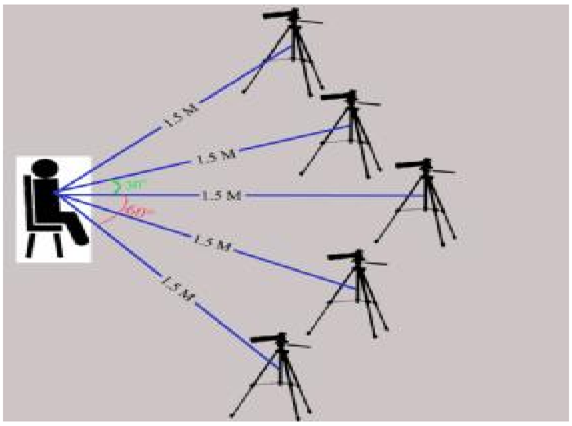

Figure 2: Five photographs were taken. One frontal , two at 60° to the right and left and two at 30° to the right and left.

Table 1: Anthropometric linear measurements used in our study

	Measurement	Landmarks		Measurements	Landmarks
1	Forehead height	Trichion-Nasion (Tr-N)	10	Nasal tip protrusion	Subnasale-Pronasale (Prn-Sn)
2	Face height	Nasion-Menton (N-Me)	11	Mouth Width	Cheilion-Cheilion (Ch-Ch)
3	Intercanthal width	Endocanthion-Endocanthion (En-En)	12	Upper lip height	Subnasale-Stomion (Sn-Sto)
4	Right eye fissure width	Endocanthion-Exocanthion (En-Ex)	13	Lower lip height	Stomion-Sublabiale (Sto-Sl)
5	Biocular width	Exocanthion-Exocanthion (Ex-Ex)	14	Lower facial third height	Subnasale-Menton (Sl-Me)
6	Face width	Zygion-Zygion (Zy-Zy)	15	Right ear height	Superaurale-Subaurale (Sa-Sba)
7	Skull base width	Tragion-Tragion (T-T)	16	Right ear width	Preaurale-Postaurale (Pra-Pa)
8	Bigonial width	Gonion-Gonion (Go-Go)	17	The height of vermlilion exposure of the upper lip	LabialeSuperius-Stomion-(Ls-Sto)
9	Nose width	Alare-Alare (Al-Al)	18	The height of vermlilion exposure of the lower lip	Stomion-LabialeInferiurs (Sto-Li)

Table 2: Comparison of Photomodeler system to direct anthropometry.[a]

Variables	Direct Anthropometry		Photomodeler		MD[b]	T - value	P - value[c]
	Mean	SD	Mean	SD			
Tr – N	52.88	4.13	53.95	4.96	-1.06	-1.9	.068 (ns)
N – Me	120.4	8.74	121.53	8.9	-1.13	-1.93	.063 (ns)
En – En	30.27	3.24	32.19	2.8	-1.93	-5.61	.000*
En – Ex	34.05	2.36	33.53	2.27	0.52	1.62	.116 (ns)
Ex – Ex	97.65	6.38	98.69	6.04	-1.04	-1.93	.063 (ns)
Zy – Zy	128.3	8.47	129.33	7.6	-1.03	-1.84	.075 (ns)
T – T	135.55	8.2	139.25	8.71	-3.7	-11.04	.000*
Go – Go	107.47	9.67	109.96	9.13	-2.5	-4.36	.000*
Al – Al	35.38	2.75	35.08	3.37	0.3	1	.324 (ns)
Prn – Sn	20.93	1.99	20.63	2.3	0.3	1.15	.258 (ns)
Ch – Ch	52.92	3.77	52.54	4.22	0.38	1.18	.248 (ns)
Sn – Sto	20.5	2.07	21.71	2.32	-1.21	-6.04	.000*
Sto – Sl	18.02	1.94	19.03	2.16	-1.02	-2.79	.009*
Sn – Me	64.85	6.26	65.38	6.31	-0.53	-1.78	.086 (ns)
Ls - Sto	7.1	1.49	7.44	1.65	-0.34	-1.96	.059 (ns)
Sto – Li	8.57	1.71	8.97	1.95	-0.41	-1.62	.116 (ns)
Pra – Pa	29.73	2.63	30.96	2.58	-1.22	-6.17	.000*
Sa – Sba	62.65	4.14	63.54	4.38	-0.89	-2.67	.012*

[a]: all variables in mm; [b]: MD = mean difference in mm.
[c] : P value from paired sample T-test; * : Significance (P < .05); ns: non-significant.

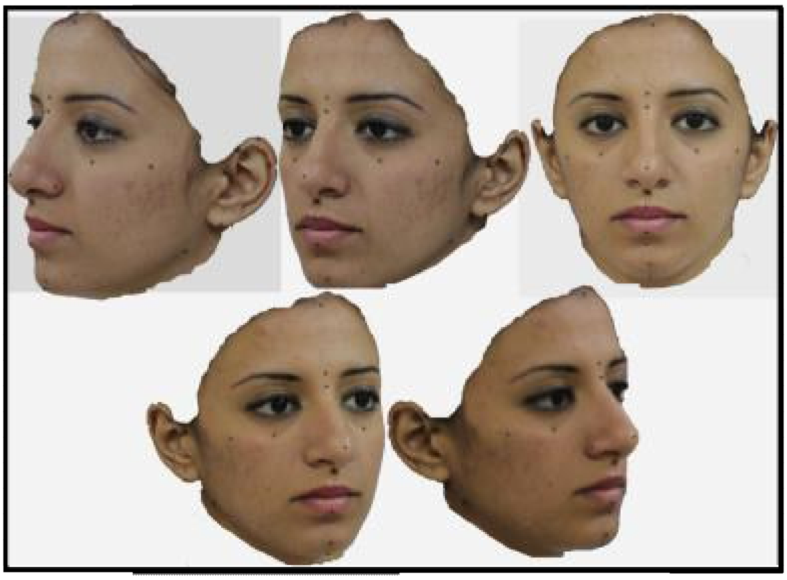

Figure 3: Five photographs resulted from camera configuration shown in figure 2.

Table 3: Precision of tracings, re-performed after 1 month on same photographs[a]

Variables	MD[b]	P[c]value	MAD[d]	TEM[e]	REM[f]
Tr – N	0	0.973 (ns)	0.42	0.38	0.01
N – Me	0.22	0.153 (ns)	0.66	0.58	0.01
En – En	0.04	0.824 (ns)	0.81	0.68	0.03
En – Ex r[c]	-0.03	0.901 (ns)	0.77	0.81	0.02
Ex – Ex	0.29	0.359 (ns)	1.33	1.19	0.01
Zy – Zy	-0.02	0.905 (ns)	0.77	0.63	0.01
T – T	-0.15	0.505 (ns)	1.02	0.87	0.01
Go – Go	0.01	0.970 (ns)	0.83	0.68	0.01
Al – Al	0.13	0.125 (ns)	0.37	0.34	0.01
Prn – Sn	-0.01	0.909 (ns)	0.4	0.33	0.02
Ch – Ch	0.05	0.603 (ns)	0.46	0.36	0.01
Sn – Sto	-0.21	0.184 (ns)	0.56	0.61	0.03
Sto – Sl	-0.04	0.787 (ns)	0.6	0.61	0.03
Sn – Me	0.1	0.320 (ns)	0.44	0.37	0.01
Ls - Sto	0.05	0.563 (ns)	0.4	0.35	0.05
Sto – Li	0.08	0.384 (ns)	0.44	0.36	0.05
Pra – Pa r[c]	-0.04	0.826 (ns)	0.62	0.63	0.02
Sa – Sba	0.1	0.596 (ns)	0.7	0.69	0.01

Table 4: Precision of Photomodeler when using a different set of photographs[a]

Variables	MD[b]	P[c]value	MAD[d]	TEM[e]	REM[f]
Tr – N	0.31	0.35	1.59	1.26	0.03
N – Me	0.16	0.7	1.97	1.57	0.02
En – En	0.22	0.63	2.25	1.74	0.07
En – Ex	-0.52	0.24	2.29	1.68	0.07
Ex – Ex	0.24	0.64	2.62	1.93	0.03
Zy – Zy	0.34	0.55	2.83	2.15	0.02
T – T	0.74	0.17	2.84	2.07	0.02
Go – Go	-0.19	0.69	2.54	1.85	0.02
Al – Al	0.1	0.48	0.66	0.55	0.02
Prn – Sn	0.1	0.46	0.62	0.5	0.03
Ch – Ch	-0.2	0.22	0.75	0.62	0.01
Sn – Sto	-0.19	0.41	1.11	0.9	0.05
Sto – Sl	-0.05	0.81	1.07	0.82	0.06
Sn – Me	-0.01	0.96	1.07	0.96	0.02
Ls - Sto	0.04	0.79	0.68	0.51	0.09
Sto – Li	0.04	0.81	0.73	0.57	0.08
Pra – Pa	-0.36	0.7	1.42	1.22	0.05
Sa – Sba	0.03	0.79	2.23	1.84	0.04

[a]: all varaibles in mm; b: MD = Mean difference. [c]: P value from paired sample t-test;significance (P< .05)[d]: MAD = mean absolute differene[e]: TEM = technical error of measurement.[f]: Rem = relative error magnitude.

DISCUSSION

Accuracy of Photomodeler

Our results suggest good agreement between measurements derived through Photomodeler system and those obtained via direct anthropometry. Notwithstanding the fact that the means of seven variables from eighteen showed significant difference when measured by the two methods, the difference was generally below two millimeter (which is considered clinically acceptable) except for two variables (T-T and Go-Go).

Two of the distances that showed significant differences were (T-T) and (Go-Go). This is in agreement with Weinberg et al. (21) and de Menezes et al. (14) and can be explained by the way Photomodeler works. The software generate the three dimensional position of any landmark by analyzing its two dimensional position on multiple photographs in a process called triangulation. If any landmark is missing from any photograph, the software gave us an approximated location of the missed landmark in that picture to complete the geometric 3D reconstruction. Since Tragus and Gonion landmarks generally don't show on frontal photographs (which is the reference photograph) their accuracy was affected. The same argument can be used to explain the significant difference for ear width (Pra-Pa) and ear height (Sa-Sba). However another factor could be the difficulty in locating landmarks on the ear because of the obscurity of the image, which is attributed to the subject's hair or helix of the ear casting a shadow on the ear [(25)]. Both Majid et al. [(26)] and Wong et al. [(13)] found that the presence of hairs may cover some landmarks, resulting in some missed values or in increased errors. In fact even with the most complicated systems, similar error magnitude has been reported for ear measurements [(27, 28)].

Two other distances that proved inaccurate are upper lip length (Sn-Sto) and lower lip length (Sto-Sl). Similar results have been observed by other authors [(21, 25)]. This error could be due to patient subtle movement during image taking. 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. This will especially affect distances that cross the labial fissure (ie, stomion). Even breathing could possibly affect the position of those landmarks.

Inaccuracies were also noted for intercanthal width (En-En). This distance was problematic in previous studies [(28, 29)]. Endocnathion (En) together with Exocnathion (Ex) andStomion (Sto) landmarks were not marked with eyeliner before measurement. Furthermore, regarding the (En-En), the inaccuracies could be partially related to direct caliper measurement rather than the Photomodeler system. This possibility seems quite reasonable taking into consideration that this asmall and rather uncomfortable measurement for subjects, due to sensitivity of the eyes to the caliper points. Clearly this limitation is not present with Photomodeler.

Generally measurements obtained by Photomodeler were larger than those obtained by direct caliper. The means of 14 of 18 distances (including all significant ones) measured by Photomodeler were larger than those obtained by calipers. Although the difference was minimal in most cases it may indicate a systematic bias inherited in this method when compared with direct anthropometry. This trend for underestimation could be explained by considering the very nature of direct anthropometry which, by definition, requires physical contact with the soft tissues of the face, whereas indirect anthropometry does not. These soft tissue structures could be compressed and may be easily distorted during direct measurements [(28)].

Precision of Photomodeler

Our data suggest excellent reproducibility for the process of retracing the same photographs in Photomodeler. There was no systematic error because all T-tests were not significant. To quantify random error we have used three precision estimates MAD, TEM and REM. It is clear that estimates of error magnitude (MAD and TEM) tended to be higher in distances of greater size while the reverse is true for REM, which seems to be higher in small distances. This is consistent with what have been found by other authors [(21, 30)]. We can also notice that (Ex-Ex) had the highest MAD and TEM followed by (T-T) and (Go-Go). On the other hand the highest REM values can be found in (Ls-Sto) and (Sto-Li) followed by (Sn – Sto), (Sto-Sl) and (En-En). We can conclude that theses seven distances had the lowest precision among the others in Photomodeler. Except for (T-T) and (Go-Go) there is a common factor among them : they all involve landmarks which had not been marked with black liquid eyeliner this confirms what have been previously found that prior marking increases the precision of indirect anthropometry [(13, 21)]. Indeed remarking the same photographs in Photomodeler in the presence of black dots from liquid eyeliner was not a difficult task. The reason may be attributed to the fact that we had a very good quality high resolution photographs that we could easily zoom in multiple times and mark exactly in the center of previously marked black dot.

Precision using a second set of photographs

All three precision estimates increased when we used a second set of photographs but still there was no significant difference for any variable. This is in agreement with other studies[(14)] and it was actually expected because in addition to the error associated with Photomodeler there is an error attributed to human error in landmark identification [(31)]. The same trend of higher MAD and TEM for greater variable and higher REM for lesser variables has been maintained. The effect of previous marking of landmarks with liquid eyeliner is also clearly demonstrated here with all distances that involve (Ex, En, and Sto) have high

MAD and TEM values or high REM values which indicates low precision. In addition, low precision has been demonstrated in (Zy-Zy) and (Go-Go). These two distances involve Zygion and Gonion landmarks which are Bony landmarks that require physical palpation for proper identification. Thus there is inherent difficulty in locating these landmarks [17]. Ear height (Sa-Sba) and cranial base width also proved problematic with high MAD values. The possible reason behind this has been explained previously.

Even though our results prove that the accuracy and precision of Photomodeler system are well within the acceptable level (2 – 3mm) cited in the anthropometric literature [22, 32], when we compare it with other Stereophotogrammetry systems used in other studies [13,28,33], it seems that its accuracy and precision are inferior to those more sophisticated and much more expensive systems. These complicated systems such as Genex and 3dMDface require a generous place to install them and use up to eight specialized high resolution cameras that take the required photographs within milliseconds, substantially reducing error resulting from patient movement. Photomodeler accuracy could be increased by using more than one camera and taking the required photographs simultaneously, however this will also increase the cost of the system.

It can be concluded that Photomodeler system can be used to measure facial characteristics with fairly good accuracy and fairly good congruence with traditional anthropometry. The system also has a clinically acceptable level precision.

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