Scientific Foundation SPIROSKI, Skopje, Republic of Macedonia
Open Access Macedonian Journal of Medical Sciences. 2021 May 14; 9(D):54-60.
https://doi.org/10.3889/oamjms.2021.6006
eISSN: 1857-9655
Category: *D - Dental Sciences*
Section: *Orthodontics*

Accuracy and Reliability of Kinect Motion Sensing Input Device's 3D Models: A Comparison to Direct Anthropometry and 2D Photogrammetry

Ahmed Mangoud Badr[1]*, Wael M. Mubarak Refai[2], Mohamed Gaber El-Shal[3], Ahmed Nasef Abdelhameed[3]

[1]Department of Orthodontics, Faculty of Dentistry, Aswan University, Tingar, Egypt; [2]Department of Orthodontics, Faculty of Dentistry, Minia University, Dean of Faculty of Dentistry, Aswan University, Tingar, Egypt; [3]Department of Orthodontics, Faculty of Dentistry, Minia University, Minya, Egypt

Edited by: Aleksandar Iliev
Citation: Badr AM, Refai WMM, El-Shal MG, Abdelhameed AN. Accuracy and Reliability of Kinect Motion Sensing Input Device's 3D Models: A Comparison to Direct Anthropometry and 2D Photogrammetry. Open Access Maced J Med Sci. 2021 May 14; 9(D):54-60. https://doi.org/10.3889/oamjms.2021.6006
Keywords: Direct anthropometry; Three-dimensional Models; Photogrammetry; Motion sensing input device; Kinect
***Correspondence:** Ahmed Mangoud Badr, Department of Orthodontics, Faculty of Dentistry, Aswan University, Tingar, Egypt. E-mail: dr.mangoud@gmail.com
Received: 12-Mar-2021
Revised: 30-Apr-2021
Accepted: 04-May-2021

Funding: This research did not receive any financial support
Competing Interests: The authors have declared that no competing interests exist

Abstract

AIM: This study aims to evaluate the accuracy and reliability of Kinect motion sensing input device's three-dimensional (3D) models by comparing it with direct anthropometry and digital 2D photogrammetry.

MATERIALS AND METHODS: Six profiles and four frontal parameters were directly measured on the faces of 80 participants. The same measurements were repeated using two-dimensional (2D) photogrammetry and (3D) images obtained from Kinect device. Another observer made the same measurements for 30% of the images obtained with 3D technique, and interobserver reproducibility was evaluated for 3D images. Intraobserver reproducibility was evaluated. Statistical analysis was conducted using the paired samples t-test, interclass correlation coefficient, and Bland-Altman limits of agreement.

RESULTS: The highest mean difference was 0.0084 mm between direct measurement and photogrammetry, 0.027 mm between direct measurement and 3D Kinect's models, and 0.018 mm between photogrammetry and 3D Kinect's. The lowest agreement value was 0.016 in the all parameter between the photogrammetry and 3D Kinect's methods. Agreement between the two observers varied from 0.999 Sn-Me to 1 with the rest of linear measurements.

CONCLUSION: Measurements done using 3D Images obtained from Kinect device indicate that it may be an accurate and reliable imaging method for use in orthodontics. It also provides an easy low-cost 3D imaging technique that has become increasingly popular in clinical settings, offering advantages for surgical planning and outcome evaluation.

Introduction

After the introduction of the soft tissue paradigm in orthodontics, orthodontic approaches established on the positive and negative characteristics of the facial soft tissues replaced the orthodontic diagnosis and treatment planning based on dental and skeletal structures [1]. If the soft tissues paradigm was objectively evaluated, efficient treatment planning can be produced, and the patient can be accurately assessed at the end of the treatment [2]. Various methods have been used to measure facial soft tissues such as direct anthropometry [3], two-dimensional (2D) photogrammetry [4], lateral cephalometry [5], cone-beam computed tomography (CBCT), and surface scanning methods (laser scanning, moiré topography, and the three-dimensional [3D] stereophotogrammetric method) [6], [7], [8]. Direct anthropometric measurement is positively a reliable and affordable method. Farkas *et al*. [3] conducted significant studies to create a large database of direct anthropometric measurements that can be used for facial measurements. Direct anthropometry, though considered as the gold standard for facial measurements, has a number of disadvantages; for example, it consumes time and requires patient compliance [9]. Frontal and profile photographs are generally used for photogrammetric measurement. On the one hand, 2D images (photograph, lateral cephalometry) are a snapshot of a dynamic object; therefore, they require cooperation only during acquisition and are easier to obtain than direct measurement [10]. When using 2D imaging methods, on the other hand, magnification and distortion issues are possible to be found, and many variables can affect the standard of measurement, such as illumination variations and object-camera distance. Another disadvantage to this technique is that significant insufficiencies may occur during the evaluation of the 2D cross-sectional images of a 3D object [11]. The limitations of previously mentioned methods were regulated using methods such as CBCT and laser scanners [12]. Because of the radiation used, computed tomography is a highly expensive and invasive product [13]. In the laser surface scanning method, if the time used for scanning is long, motion artifacts can appear [14]. That's the reason why, to overcome these limitations, 3D stereophotogrammetry was developed. With this method, 3D images are acquired by combining photographs captured from various angles with synchronous digital cameras. The advantages of this method are the lack of motion artifacts because of the short imaging time, high color resolution, and the opportunity for administration without harming patients for repeated analyses, quick configuration, imaging through advanced software, ease of archiving, and 3D storage of patient images [15], [16]. This method can turn out to be a routine process in orthodontic practice when 3D stereophotogrammetry devices become affordable and accessible. Therefore, the present study aims to compare three measurement methods and evaluate the accuracy of 3D by comparing it with direct anthropometry. Furthermore, the study also intends to evaluate the intraobserver and interobserver reliability of 3D stereophotogrammetric measurements in 10 linear and six angular measurements.

Materials and Methods

After approval was obtained from Ethical Committee of Faculty of Dentistry, Minia University, the participants were informed verbally and in writing before the study, and volunteer consent forms were collected from all participants.

Sample

The present study was conducted with 80 participants between 25 and 45 years old. For an effect size of 0.4 at a 0.05 significance level, there could be more than 90% power with a sample size of 80. The mean age of the participants was 31.7 ± 3.4 years, and there were 48 males (60%) and 32 females (40%). The study included people who had no previous facial surgery, no craniofacial defects, and no specific scar tissue on the face. The 2D and 3D images were acquired within the same day, and direct measurements were made on the day of image acquisition. Measurements of 2D and 3D images were randomly made on a different day from direct measurements to avoid any chances of interference.

Direct measurements

By inspection and palpation, morphologic points required for linear measurements were determined and were then marked on the face. During the determination and measurement of the points, it was made sure that the patients were relaxed and seated with a natural head position and relaxed lips. A digital millimeter caliper (sliding) was applied to directly measure the distance between the four different points in the frontal plane (exocanthion, endocanthion, cheilion, and alare base) and the distance between seven different points in the sagittal plane (tragus, exocanthion, nasion, pronasale, subnasale, stomion, and menton). Measurements were taken under the same room conditions with the same illumination (Table 1).

Table 1: Anthropometric landmarks and definition of linear distances

Abbreviation	Landmarks	Definition
Tr-Ex	Tragus, exocanthion (mm)	Sagittal linear measurement from tragus to exocanthion
N-Prn	Nasion, pronasal (mm)	Vertical linear measurement from nasion to pronasale
N-Sn	Nasion, subnasal (mm)	Vertical linear measurement of upper facial dimension as measured from nasion to subnasale
Sn-St	Subnasal, stomion (mm)	Vertical linear measurement of overall upper labial height from subnasal to stomion
Sn-Prn	Subnasal, pronasal (mm)	Sagittal linear measurement of nasal tip protrusion from subnasal to pronasal
Sn-Me	Subnasal, menton (mm)	Vertical linear measurement of lower facial dimension as measured from subnasale to stomion
Ex-Ex	Exocanthion right, exocanthion left (mm)	Transverse linear measurement of biocular (lateral canthal) width from exocanthion right, or Ex (R), to exocanthion left, or Ex (L)
En-En	Endocanthion right, endocanthion left (mm)	Transverse linear measurement of intercanthal distance from endocanthion right, or En (R), to endocanthion left, or En (L)
Ch-Ch	Cheilion right, cheilion left (mm)	Transverse linear measurement of mouth width from cheilion right, or Ch (R), to cheilion left, or Ch (L)
Al-Al	Alare right, alare left (mm)	Transverse linear measurement of nasal width from alare right, or Al (R), to alare left, or Al (L)
NFA	Nasion, glabella, pronasale (u)	Angular measurement from nasion to glabella to pronasale (nasofrontal angle)
NLA	Columella. subnasale, labium superior (u)	Angular measurement from columella to subnasale to labium superior (nasolabial angle)
MLA	Labium inferior, supramental, pogonion (u)	Angular measurement from labium inferior to supramental to pogonion (mentolabial angle)
Middle 1/3	Nasion, tragus, subnasale (u)	Angular measurement from nasion to tragus to subnasale (angle of medium facial third)
Lower 1/3	Subnasale, tragus, menton (u)	Angular measurement from subnasale to tragus to menton (angle of inferior facial third)
Conv	Glabella, subnasale, pogonion (u)	Angular measurement of soft tissue profile from glabella to subnasale to pogonion

Cont Table 1. Anthropometric landmarks and definition of linear distances.

2D photogrammetric acquisition and measurements

All images were obtained by placing the participants in the same position as in the direct measurement, frontal and profile photographs were captured under the same illumination using a professional camera (Nikon D $5600_{18\text{-}55}$ VR) AF-P DX NIKKOR 18–55 mm f/3.5–5.6G VR

A millimeter ruler was used to avoid magnification errors, and the ruler was carefully held in the same plane with the frontal and profile measurement points. All photographs were transferred to a computer, and calibration procedures were performed using View Box 4.0 software (dHAL Software, Kifissia, Greece). Ten linear and six angular measurements were made on the images.

2D Models Photogrammetric Acquisition and Measurements

3D scanner A Microsoft Kinect v2 module was utilized as the 3D scanner is used for gesture recognition and can capture raw 3D scan data. It has a 1080p camera operating at 30 Hz which can capture a regular 2D image. Its depth sensor operates at 30 Hz and has a 512×424 sensor. The horizontal field of view is 70 degrees, while the vertical is 60 degrees. Hardware configuration uses a good graphics processing capabilities laptop (RAM > 4GB, dual-core, or multicore CPU) to handle the 3D data acquisition and rendering. A Lenovo IdeaPad L340 Gaming laptop was used with an NVIDIA GeForce GTX 1650. Furthermore, a frame rate of 16–20 fps was used. Software Better performance is obtained with using Windows 10 operating system and using a 3D scanning software as Microsoft 3D scan. Kinect software development kit (SDK) is also used for capturing raw 3D data. The 3D builder application is used to create the mesh, and MeshLab is used to clean, repair, and smoothen the mesh. Data were stored in ply format. All participants were placed in same position to capture the images and Kinect one (Microsoft Kinect scanner version 2) motion sensing input device was used to generate the 3D model.

Statistical analysis of the data

The collected data were coded, listed, and statistically analyzed using SPSS program (Statistical Package for the Social Sciences) software version 25.

Descriptive statistics were done for parametric (normally distributed) quantitative data by mean, standard deviation (SD), and minimum and maximum of range and for qualitative data by frequency and percentage. Distribution of the data was done by Kolmogorov–Smirnov test. Testing of agreement between each 2 methods was made by Bland-Altman plot followed by paired-samples t test.

Reliability between different methods and intraobserver and interobserver agreement was made by interclass correlation coefficient (ICC).

The level of significance was taken at $p \leq 0.05$.

The results were determined to be clinically acceptable at an arbitrary value of 1 mm between two different measurements. In the 3D images, to evaluate the interobserver agreement, a different observer made 30% of the measurements similar to the first observer. In addition, to indicate the intraobserver agreement, both observers made the same measurements 30 days after the initial measurements. Intraobserver and interobserver agreement for the 3D method were assessed similarly using the paired samples t-test, ICC, and the Bland-Altman limits of agreement. The results were stated to be clinically acceptable at an arbitrary value of 2 mm between observers and within an observer. The statistical significance level was 0.05 in all statistical analyses.

Results

Linear measurements

a. Tr-Ex

There was no statistically significant difference was found between (Anthro), (2D), and (3D) measurements where ($p = 0.345$).

b. B) N-Prn

There was a statistically significant difference was found between (Anthro), (2D), and (3D) measurements where ($p < 0.001$).

A statistically significant difference was found between (Anthro) and each of (2D) and (3D) measurements where ($p = 0.015$) and ($p < 0.001$).

Furthermore, a statistically significant difference was found between (2D) and (3D) measurements where ($p < 0.001$).

c. N-Sn

There was a statistically significant difference was found between (Anthro), (2D), and (3D) measurements where ($p = 0.047$).

A statistically significant difference was found between (Anthro) and each of (2D) and (3D) measurements where ($p = 0.028$) and ($p = 0.046$).

While no statistically significant difference was found between (2D) and (3D) measurements where ($p = 0.722$).

d. Sn-St

There was no statistically significant difference which was found between (Anthro), (2D), and (3D) measurements where ($p = 0.219$).

e. Sn-Prn

There was a statistically significant difference which was found between (Anthro), (2D), and (3D) measurements where ($p = 0.023$).

A statistically significant difference was found between (Anthro) and each of (2D) and (3D) measurements where ($p = 0.004$) and ($p = 0.012$).

While no statistically significant difference was found between (2D) and (3D) measurements where ($p = 0.094$).

f. Sn-Me

There was a statistically significant difference which was found between (Anthro), (2D), and (3D) measurements where ($p = 0.032$).

A statistically significant difference was found between (3D) and each of (Anthro) and (2D) measurements where ($p = 0.025$) and ($p = 0.021$).

While no statistically significant difference was found between (Anthro) and (2D) measurements where ($p = 0.247$).

g. Ex-Ex

There was a statistically significant difference which was found between (Anthro), (2D), and (3D) measurements where (p = 0.010).

A statistically significant difference was found between (3D) and each of (Anthro) and (2D) measurements where (p = 0.018) and (p = 0.007).

While no statistically significant difference was found between (Anthro) and (2D) measurements where (p = 0.926).

h. En-En

There was no statistically significant difference was found between (Anthro), (2D), and (3D) measurements where (p = 0.475).

i. Ch-Ch

There was no statistically significant difference was found between (Anthro), (2D), and (3D) measurements where (p = 0.537).

j. Al-Al

There was no statistically significant difference which was found between (Anthro), (2D), and (3D) measurements where (p = 0.464) as shown in Table 2.

Table 2: Relationship between three groups in different linear parameters

Measurement	Groups	Min.	Max.	Mean	S.D.	p-value
Tr-Ex	Anthro	65.210	79.320	70.027	3.379	0.345ns
	2D	65.160	79.280	70.027	3.377	
	3D	65.160	79.280	70.030	3.382	
N-Prn	Anthro	41.890	63.150	55.350	5.798	<0.001*
	2D	41.890	63.200	55.359	5.797	
	3D	41.920	63.260	55.377	5.794	
N-Sn	Anthro	45.980	74.550	56.912	7.259	0.047*
	2D	45.980	74.550	56.915	7.257	
	3D	45.980	74.550	56.916	7.257	
Sn-St	Anthro	17.150	29.360	19.652	2.632	0.219ns
	2D	17.150	29.400	19.653	2.632	
	3D	17.150	29.400	19.656	2.631	
Sn-Prn	Anthro	17.300	25.960	19.302	2.061	0.023*
	2D	17.320	25.960	19.309	2.059	
	3D	17.320	26.000	19.320	2.061	
Sn-Me	Anthro	56.090	73.610	61.024	4.799	0.032*
	2D	56.140	73.600	61.026	4.793	
	3D	56.140	73.610	61.029	4.793	
Ex-Ex	Anthro	104.320	127.340	109.888	3.865	0.010*
	2D	104.320	127.340	109.888	3.861	
	3D	104.320	127.350	109.900	3.861	
En-En	Anthro	24.320	35.620	29.644	2.044	0.475ns
	2D	24.320	35.600	29.643	2.043	
	3D	24.320	35.600	29.645	2.046	
Ch-Ch	Anthro	41.420	59.380	49.538	3.514	0.537ns
	2D	41.400	59.400	49.541	3.513	
	3D	41.500	59.400	49.539	3.511	
Al-Al	Anthro	30.450	39.980	35.542	2.330	0.464ns
	2D	30.450	39.980	35.544	2.330	
	3D	30.450	39.980	35.545	2.329	

S.D.: Standard deviation. Min.: Minimum value. Max.: Maximum value. *: Significant (p ≤ 0.05), ns: Non-significant (p > 0.05).

Angular measurements

a. NFA

No statistically significant difference was found between (2D) and (3D) groups where (p = 0.581).

b. NLA

A statistically significant difference was found between (2D) and (3D) groups where (p = 0.043).

c. MLA

No statistically significant difference was found between (2D) and (3D) groups where (p = 0.802).

d. Middle third

No statistically significant difference was found between (2D) and (3D) groups where (p = 0.365).

e. Lower third

No statistically significant difference was found between (2D) and (3D) groups where (p = 0.109).

f. Conv

No statistically significant difference was found between (2D) and (3D) groups where (p = 0.582) as shown in Table 3.

Table 3: Relationship between three groups in different angular parameters

Measurement	Groups	Min.	Max.	Mean	S.D.	p-value
NFA	2D	126.700	134.100	130.415	1.242	0.581ns
	3D	126.700	134.100	130.419	1.238	
NLA	2D	92.900	98.000	95.105	1.279	0.043*
	3D	92.900	98.000	95.126	1.290	
MLA	2D	116.800	124.300	120.136	2.224	0.802ns
	3D	116.500	124.500	120.139	2.223	
Middle third	2D	23.000	29.500	26.554	1.620	0.365ns
	3D	23.600	29.500	26.530	1.617	
Lower third	2D	30.500	39.100	34.344	2.353	0.109ns
	3D	30.500	39.100	34.359	2.340	
Conv	2D	163.800	178.900	169.589	3.554	0.582ns
	3D	163.800	178.900	169.594	3.533	

S.D.: Standard deviation. Min.: Minimum value. Max.: Maximum value. *: Significant (p≤0.05), ns: Non-significant (p>0.05).

Interobservers and Intraobservers' reliability

Reliability coefficient (ICC), interobserver, and intraobserver agreement of anthropometric method

Both inter- and intraobserver measurements showed extremely high (ICC) in all linear measurements where (ICC) was (1) in all parameters except for (Sn-Me) which was (0.999), which all states an extraordinarily strong reliability and agreement between readings.

Reliability coefficient (ICC), interobserver, and intraobserver agreement of 2D method

Both inter- and intraobserver measurements showed extremely high (ICC) in both linear and angular measurements where (ICC) was (1) in all parameters except for (NFA) and (lower third) parameters in inter measurements and in (NFA), (NLA), and (lower third) parameters in intra measurements where (ICC) were (0.999), which all states an extraordinarily strong reliability and agreement between readings.

Reliability coefficient (ICC), interobserver, and intraobserver agreement of 3D method

Both inter- and intraobserver measurements showed extremely high (ICC) in both linear and angular measurements where (ICC) was (1) in all parameters, which all states an extraordinarily strong reliability and agreement between readings.

Discussion

The present study evaluated the accuracy and reliability of 3D models of the Kinect. A very high level of agreement was found between direct anthropometry, photogrammetry, and 3D models since the highest mean difference was 0.5 mm. For intraobserver and interobserver reliability, the mean difference was <1 mm in linear measurements and <2° for angular measurements in 3D images. These values were considered to be clinically insignificant. In addition to clinical evaluation, quantitative evaluations performed in facial soft tissues are necessary for assessing treatment goals and treatment results. CBCT can be used for three dimensions soft tissue analysis despite having several disadvantages [12]. Besides, the measurement difference between CBCT and 3D models appeared to be clinically insignificant [17]. The use of Kinect's 3D models, hence, is deemed adequate in imaging soft tissues and measuring facial soft tissues. The direct anthropometry method is not routinely used in clinical practice; however, it is vital to provide actual measurement results when accurate and careful measurements are made. In this study, the mean difference was found to be 0.5 mm between these two methods. The validity of 3D models was methodologically evaluated using devices of different types and brands. Such studies have found >1 mm mean difference between different methods and between intraobserver and interobserver measurement points [9], [17], [18], [19], [20]. In the literature, deviations are reported to be mostly caused by observer errors during the placement of anthropometric points [21], [22]. Plooij *et al*. [23] found intraobserver reliability varying between 0.90 and 0.99. They found interobserver agreement above 0.8 in most points and stated that reproducibility was substantially lower than 0.5 mm. Khambay *et al*. [24] reported that the grand mean of the precision calculated across subjects along all axes for all landmarks was 0.827 mm. Lubbers *et al*. [25] found a reproducibility error of 0.5 mm. Lu¨bbers *et al*. examined the precision and accuracy of 3D stereophotogrammetry and declared a mean global error between 0.1 and 0.5 mm. The greatest and most significant difference was 1.42 mm in the N-Prn measurement for interobserver agreement; however, the difference was 2 mm for any parameters. The highest interobserver agreement was in the Al-Al measurement (95% CI, –0.21, 0.56; mean 5 0.17 mm). Agreement between measurements was above 0.9 in all measurements based on ICC results. These findings are consistent with the studies by Aldridge *et al*. [19], Wong *et al*. [9], and Schaaf *et al*. [26]. According to Heike *et al*. [27] and Junqueira-Júnior *et al*. [28], the intra-rater reliability correlation coefficients for the 3D stereophotogrammetric images were ≥0.95 for 26 of the 30 measurements and mean absolute differences were 1 mm. The present study found agreement between 2D photogrammetry and other methods, which suggests that 2D measurements can be safely used in images collected with accurate technique and attention. Farkas *et al*. [29] and Wellens *et al*. [30] reported that, by the distortions in photogrammetry, the difference between direct anthropometry and 2D photogrammetry may be caused. It seems crucial to make the calibration in the same plane as the measuring points in 2D measurements. In addition, it is possible to reuse such data when necessary and to use such data by comparing it with other methods. For reliability, it is pivotal to have a clear acquisition of the facial regions to be measured. There may be image errors in the ear region (e.g., tragus) in systems that can capture image up to 180u. The Kinect device, which was used in the present study, can be converted into different modules according to the desired imaging area. In the present study, 360u images were acquired using five modular units (front: Two, rear: Two, and top: One) to avoid image loss all over the face, including the ear region. In the case of image distortions, particularly in the ear region, acquisition was repeated depending on the facial morphology. What comes as a priority of contemporary orthodontic diagnosis and treatment planning is evaluating the properties of facial soft tissue clinically and quantitatively. Many imaging techniques have been adopted to assess facial soft tissues [31], but 3D Kinect's models attracted more attention because of the many advantages mentioned. The reproducibility of the points determined for measurements is one of the most important factors determined for measurements. In fact, the low-range variation in the present study is known to have resulted from minor deviations that took place during the placement of the morphologic earlier. This method was concluded to be accurate and reliable to be integrated into orthodontic clinical practice. Furthermore, it is possible to process and analyze 3D Model images in different software in accordance with different clinical or research purposes.

Conclusion

- Measurements using Kinect's 3D models were consistent with both direct anthropometric and 2D photogrammetric measurements
- The high intraobserver and interobserver reproducibility suggest that this method can be reliably used
- Kinect's 3D models provide efficient and low-cost 3D models that have become increasingly popular in clinical settings, offering advantages for surgical planning and outcome evaluation.

Due to its superior gained data in relation to the conventional 2D Images, it also saves the chairside time and eliminates the need for high levels of patient compliance.

Research Ethical Approval

This study was made with the approval of the Ethical Committee of the Faculty of Dentistry, Minia University.

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