Reliability and Accuracy of Mobile 3D Scanning Technologies for the Customization of Respiratory Face Masks

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Abstract

This article compares the reliability and accuracy of face-scanning technologies used in the context of head reconstruction. The goal of this study is to provide recommendations as to which technology is suitable for customizing respiratory face masks. Two technologies will be analyzed; ARKit: Face Tracking SDK by Apple using an iPhone XR, and Structure Sensor by Occipital using the 3DSizeMe app with an iPad Pro 5th generation. As ARKit only generates a mesh on the face, the Flame AI framework is used to extrapolate the full head shape.

Reliability and accuracy were determined through a series of standard measurements taken on each reconstructed scan of a series of 48 male and female retopologised head scans obtained from the 3D Scan Store. Each head was 3D printed and scanned three times with both ARKit and the Structure Sensor. A deep-learning model was used to identify 73 standard landmarks on each face from which were derived 11 anthropometric measurements defined by the ISO 16976-2:2015 part 2. The anthropometric measurements were compared between scans of a single face for reliability and compared with the initial head form for accuracy.

Context: In 2021, the production of off-the-shelf single-use N95 masks had almost quintupled since the Covid-19 outbreak in 2019. Healthcare professionals must now wear a mask at all times when treating patients. They thus wear masks every day for extensive periods of time. The airtight seal required to guarantee efficiency sometimes requires excessive pressure depending on the morphology. This, coupled with the prolonged use, often causes discomfort and injuries. This issue led to a worldwide effort to develop custom-fitted respiratory masks. The advantage of designing a custom-made mask based on the 3D scan of the face is ergonomic and improves user comfort over extended periods of time.

Keywords: Digital anthropometry, 3D reconstruction, 3D scanning, Anthropometric measurements, Accuracy, Reliability, Cloud computing, 3D Face scan, 3D Head scan, Custom fit, Machine learning, Mobile devices, COVID-19, Respiratory Mask.

1.Introduction

Covid-19 has changed the world in many aspects. Everyone has been affected by the pandemic, for instance through limitation of physical contact, social distancing or mandatory wearing of masks to limit the spreading of the virus. Many professionals must wear masks for long periods of time because they are in contact with other people. The biggest issue is the discomfort, caused by a bad fitting of the masks **[1]**. To limit this problem, different off-the-shelf sizes are available to find the most suitable for each user. Those options focus on maintaining good airtightness, with comfort as a lower priority **[2,3].** As a result, many healthcare professionals and other people wearing N95 masks for prolonged hours report discomforts due to pressure and irritation on some parts of the face **[4]**.

In order to reduce the discomfort as much as possible, one of the solutions considered is to create custom-made masks using 3D printing. Since the beginning of the pandemic, 3D printing has solved many problems in the healthcare field. Many countries have suffered from a shortage of respiratory systems in their hospitals. Thanks to 3D printing, the impact was less severe with the printing of material like oxygen valve **[5]**. We are also seeing more and more 3D printing in the field of orthotics and prosthetics as it allows us to make customized products for each patient. Indeed, while maintaining the safety of the wearer, 3D printed masks can be easily adapted for individuals independently of their

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anthropometric features and therefore optimize comfort. The materials used for 3D printing masks also offer the ability to be sterilizable multiple times and only the filtering parts of the mask must be regularly changed, which can help reduce the plastic waste induced by the use of disposable masks **[6]**

To design these customized masks, we must capture the anthropometric features of each wearer. 3D scanners are the best solution available to us **[7]**. These last years, technologies of augmented reality and depth data processing have enabled advances in the 3D scanning field. This led to the development of several scanning solutions, each more or less reliable depending on their applications [8]. Two of them were selected in our studies: ARKit by Apple Inc. and Structure Sensor by Occipital Inc.

ARKit is a face tracking SDK by Apple Inc. available on their last generation of iPhone cameras that allows facial recognition from a depth sensor. It uses the front-facing camera and captures the information in a single shot. The face is then automatically detected by AI **[9]**. As for the Structure sensor **[10]**, it is a hardware module that can be attached to a smartphone or a tablet and must be used with Mobile apps like Shapeshift 3D Scanner to be able to guide user to scan various part of the body. However, it has been proven that low quality scans are largely due to the user. . In other words, it would be easier to use ARKit than the Structure Sensor Pro, but the latter could have a better accuracy than ARKit when it is correctly used.

Therefore, ARKit is a mobile scanning method that might be the best option for 3D scanning with great facility to use for the operators. In this study, we suggest a method to quantify the reliability and accuracy of mobile 3D scanning technologies for the customization of respiratory face masks.

2. Methods

2.1. Design of experiment

In order to quantify the reliability and accuracy of the scanning technologies, we selected a dataset that respects heterogeneity of gender, ethnic diversity and age. The "Male and female 3D head model 48 X bundle" **[11]** consists of forty-eight high resolution 3D head models, of which half are male and half are female. For each of these heads, we had to pre-treat their models to be printable in 3D. We chose to print these heads in color using the sandstone material **[12][13]**. This material is ideal for this study since it can support a minimum wall thickness of 2 mm, has an accuracy of 0.5 mm and can be used to print in color. Indeed, color is required to have a contrast on the skin and therefore improve the resulting scans. Each face was scanned three times with each of the two scanning technologies for a total of 288 acquisitions. We also conducted tests on five 3D head models from Anthropometric Data and ISO Digital Headforms to the sample.

The 3D printings were scanned with ARKit and Structure sensor. For ARKit, the scanning was made with the front camera of an iPhone XR and an iPhone 11 **[14]**. The Shapeshift 3D scanner app, which is used with the Structure sensor**,** requires scanning by a trained professional as this scanner is rear facing and meant to be operated by another person. For our study, we use the Structure Sensor Pro with an iPad Mini to scan.

Once the scanning is complete, we process each scan individually through Shapeshift 3D's scan reconstruction algorithms. ARKit provides a coarse 3D mesh geometry matching the size and shape of the face. However, the face scan doesn't cover the entire section on which a mask should be fitted. In order to extrapolate the head based on the face scan, we used the TF-Flame framework **[15]**. The AI extrapolates the features of the head to generate a new mesh and thus provides forehead, neck and head information. As for the Structure Sensor, the quality of the scan highly depends on the user. We therefore run each scan through reconstruction steps which extract the relevant structures and remove artifacts, trim the edges to avoid hair and noise, close all holes and smooth the mesh. To do so, we are using Shapeshift3D Repair algorithms **[16]**. Figure 1 presents examples of raw scans and a processed scans of a same face taken by each scanning technology

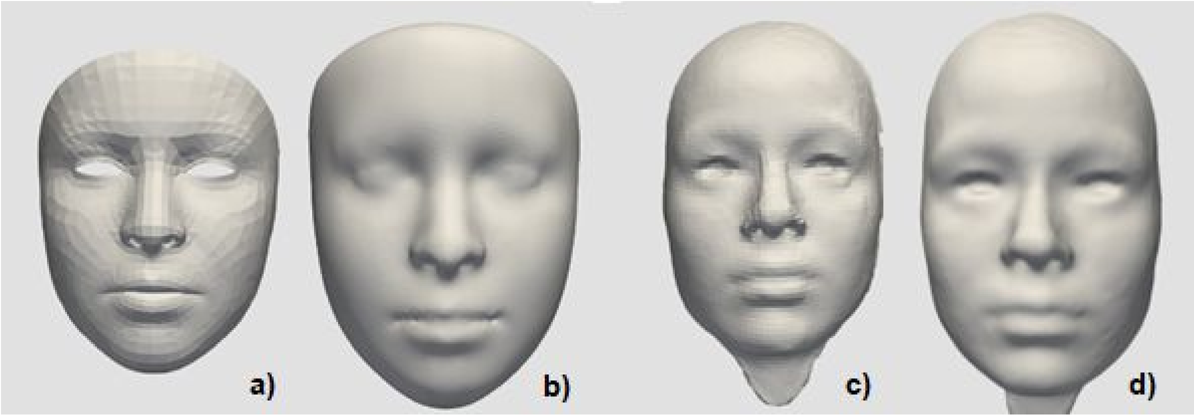

Figure 1 a) Raw ARKit scan b) Processed ARKit c) raw Structure sensor scan d) Processed Structure sensor

2.2. Data processing

To evaluate the two technologies, we base our study on two criteria, reliability and accuracy. The reliability and the accuracy of these two technologies are determined using 8 measurements, a subset of anthropometric measurements defined by the standard ISO 16976-2:2015 part 2. These measurements are taken using anatomical landmarks on the face and can be classified in two groups: Euclidean distance and geodesic distance. We obtained these landmarks using the Deep-MVLM AI algorithm **[17]**. This AI takes the 3D scan or model as an input and outputs 73 landmarks on the face. Figure 2 shows an example of landmarks on a scan done by each of the two technologies, as well as on the initial model.

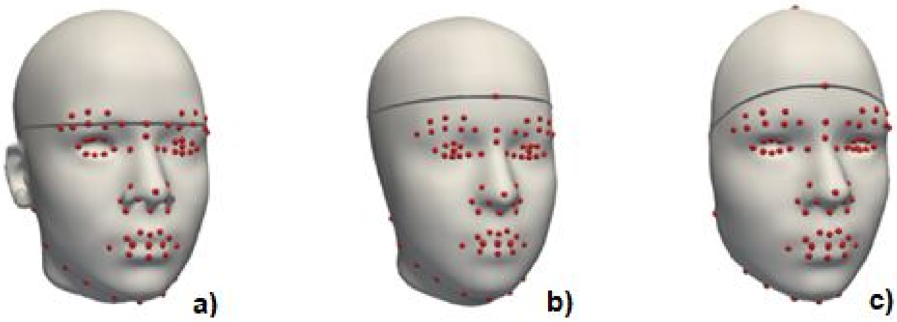

Figure 2: Landmarks from a) Headform b) ARKit c) Structure Sensor

We consider the 3D models of the dataset as the ground truth. Therefore, we can evaluate the accuracy of each technology by measuring the bias compared to the headforms. Based on the measurements taken, the Intraclass Correlation Coefficients (ICC) method is used to evaluate the reliability of each technology **[18]**. For this method, values of ICC of less than 0.5 indicate poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability. Table 1 presents the 8 measurements selected in this study for the evaluation of the accuracy and reliability.

Table 1 Anatomical measurements used for the reliability analysis

Measurement	Type of distance
1.Bigonal breadth	Euclidean distance
2.Interpupillary distance	Euclidean distance
3.Nose protrusion	Euclidean distance
4.Nose breadth	Euclidean distance
5.Nasal root breadth	Euclidean distance
6.Bitragion chin arc	Geodesic distance
7.Bitragion subnasal arc	Geodesic distance
8.Lip length	Euclidean distance

We have chosen these measurements because the differences are statistically significant in the population and relevant to the making respiratory masks. However, the data analysis showed some issues with the location of the landmarks we used for the measurement of the two bitragions. Indeed, since the ARKit scans do not have ears, IA Deep-MVLM has difficulty placing the landmarks under the ears in the right place. To solve this issue, we chose to remove these landmarks from the bitragion measurement. The measurement of bitragion now uses fewer landmarks to be calculated but is more reliable.

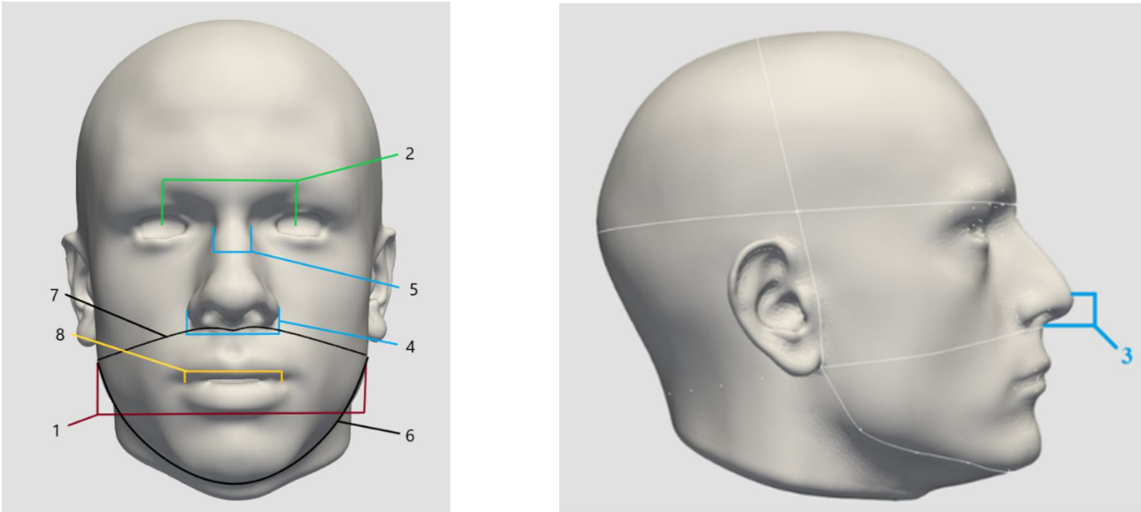

Figure 3 Measurements taken on scans

3. Result and discussion

Table 2 shows the bias on each measurement for both 3D scanning technologies of interest.

Table 2 Mean relative error to baseline for two 3D scanning technology

Measurement	**ARKit** [%]	**Structure Sensor** [%]
Bigonal breadth	5.43 ± 0.16	4.19 ± 0.32
Interpupillary distance	8.04 ± 0.70	10.56 ± 0.95
Nose protrusion	10.91 ± 0.83	4.54 ± 0.10
Nose breadth	5.62 ± 0.31	3.62 ± 0.09
Nasal root breadth	4,78 ± 0.23	3.23 ± 0.01
Bitragion chin arc	7.53 ± 0.64	7.36 ± 0.05
Bitragion subnasal arc	4.68 ± 0.17	5.53 ± 0.18
Lip length	4.82 ± 0.26	4.3 ± 0.04

This results in a total average bias of 6.48% for ARKit, and 5.41% for the Structure Sensor, indicating the latter to be more accurate. Interpupillary distance seems to have important bias for both technologies, especially for the Structure Sensor. This can be explained by the fact that the printed faces had holes instead of eyes. While ARKit automatically fills those holes, the Structure Sensor still displays them, as is shown in Figure 1. If we average the bias without interpupillary distances, we obtain an accuracy of 6.26% for ARKit and of 4.68% for Occipital. This indicates that the Structure Sensor has sufficient accuracy for 3D-printed face masks fitting. ARKit however doesn't seem to be accurate enough, especially around the nose which is a critical area for fitting a mask. This might be caused by ARKit not accurately capturing depth information. Since the depth information is generated by iPhones, it could be possible to pair it with the ARKit data to obtain a more accurate scan as structure sensor.

Table 3 presents the absolute maximum error limit on each of the measurements.

*Table 3 Absolute maximum error limit on measurements (|Bias|+1.96*SEM)*

Measurement	**ARKit [mm]**	**Structure Sensor [mm]**
Bigonal breadth	11.5	28.9
Interpupillary distance	15.2	18.6
Nose protrusion	4.77	2.42
Nose breadth	3.79	2.40
Nasal root breadth	2.85	1.49
Bitragion chin arc	12.2	13.2
Bitragion subnasal arc	9.57	8.21
Lip length	1.25	1.09

The results in Table 3 support the ones in Table 2. The Structure Sensor seems to be overall accurate enough to fit a face mask, while ARKit seems to lack depth accuracy. However, an in-depth analysis of the geodesic measurements' method would be required to validate the accuracy on the bitragion measurements.

Table 4 shows the ICC of each technology.

Table 4 Intraclass Correlation Coefficients for ARKit and Structure Sensor scan

Measurement	**ARKit**	**Structure Sensor**
Bigonal breadth	0.994	0.867
Interpupillary distance	0.872	0.967
Nose protrusion	0.962	0.964
Nose breadth	0.980	0.974
Nasal root breadth	0.945	0.920
Bitragion chin arc	0.907	0.834
Bitragion subnasal arc	0.513	0.552
Lip length	0.930	0.960

For both scanning technologies, we observe a good reliability with more than 0.7 of score on seven of the eight measurements. The average ICC is of 0.888 for ARKit and 0.880 for the Structure Sensor. The lowest ICC is observed for the bitragion measurements. These measurements are more subject to high variability since they must pass on the surface of the meshes. This makes them both sensitive to the landmarking quality, as well as the detected shortest path. We consider an ICC score over 0.75 to indicate good reliability. Both technologies therefore seem to have very good reliability for face scanning. Those results were to be expected since ARKit fits a standard mesh on each face, and the Structure Sensor is widely used in the O&P industry for custom-fitted orthotics.

Since all results are sensitive to the quality of the AI detected landmarks, we ran an ICC analysis on the initial 3D head models by processing each one thrice. Table 5 shows the resulting ICCs.

Table 5 Intraclass Correlation Coefficients for scan processing

Bigonal breadth	Interpupillary distance	Nose protrusion	Nose breadth	Nasal root breadth	Bitragion chin arc	Bitragion subnasal arc	Lip length
0.984	0.449	0.893	0.973	0.910	0.974	0.779	0.803

We observe that the interpupillary distance have a critically low ICC with 0.449, which again is caused by the models lacking eyes. The total average ICC is however of 0.846 with the interpupillary distance, and of 0.902 without. This indicates our scan processing method has good reliability. Note that additional bias may arise from the head extrapolation and the landmarking methods. Further analysis is required to quantify this bias.

4. Conclusion and further work

The aim of this study was to compare the reliability and accuracy of ARKit by Apple Inc. and Structure Sensor by Occipital Inc. used in the context of face scans for custom-fitted 3D-printed masks. Results suggest the overall reliability and accuracy of both technologies to be sufficient for this application. However, the accuracy for the measurement of the nose's protrusion were insufficient for ARKit, which has a significant impact on the fit's quality and the comfort of the mask.

From a data perspective, improvements can be made. The results suggest that the reliability can be improve for the bitragion measurements. It may be interesting to review the method of calculation of these measurements by optimizing the geodesic calculation.

As part of the head processing, the landmarking method should be improved and analyzed to better understand its induced bias. Further studies on the reliability of the AI could provide answers. Indeed, MVLM AI show a good reliability but not for all measurements. A path to improvement could be to train the model with partial model, with neither ears nor eyes.

It would also be interesting to analyze the results from a topological perspective. A registration method could be used to align the reconstructed scans with the initial models and a distance analysis could be performed on areas where a face mask would be in contact with the skin.

Finally, an improvement can be also made by using the depth data generated by the iPhone to improve the scans from ARKit. An important improvement in ARKit reliability for critical measurements would be required to make it suitable for custom-fitted masks. Due to the ease of use of the ARKit technology, we believe that this technology could greatly simplify faces scanning if accurate and reliable enough.

References

[1] PRIYA, K., VAISHALI, P. N., RAJASEKARAN, S., *et al.* Assessment of Effects on Prolonged Usage of Face Mask by ENT Professionals During Covid-19 Pandemic. *Indian Journal of Otolaryngology and Head & Neck Surgery*, 2021, p. 1-5.

[2] Centers for Disease Control and Prevention, "NIOSH Anthropometric Data and ISO Digital Headforms," accessed 23 April 2020.
[Online]. Available: https://www.cdc.gov/niosh/data/datasets/rd-10130-2020-0/default.html

[3] Government of Canada, "Safety and performance specifications for respirators during COVID-19: Guidance for Canadian manufacturers," accessed 25 August 2020. [Online]. Available: https://www.canada.ca/en/health-canada/services/drugs-health-products/covid19-industry/medical-devices/personal-protective-equipment/medical-masks-respirators/safetyperformance-specifications.html

[4] ROSNER, Elisheva. Adverse effects of prolonged mask use among healthcare professionals during COVID-19. J Infect Dis Epidemiol, 2020, vol. 6, no 3, p. 130

[5] TINO, Rance, MOORE, Ryan, ANTOLINE, Sam, et al. COVID-19 and the role of 3D printing in medicine. 3D Printing in Medicine, 2020, vol. 6, no 1, p. 1-8.

[6] SELVARANJAN, Kajanan, NAVARATNAM, Satheeskumar, RAJEEV, Pathmanathan, et al. Environmental challenges induced by extensive use of face masks during COVID-19: A review and potential solutions. Environmental Challenges, 2021, vol. 3, p. 100039.

[7] Xia, Sibei & Guo, Siming & Li, Jiayin & Istook, Cynthia. (2018). Comparison of different body measurement techniques: 3D stationary scanner, 3D handheld scanner, and tape measurement. The Journal of The Textile Institute. 110. 1-11. 10.1080/00405000.2018.1541437.

[8] BORDUAS, Jonathan, CASTONGUAY-HENRI, Aude, LAURIN, Patrick, et al. Reliability of Mobile 3D Scanning Technologies for the Customization of Respiratory Face Masks. In : Proceedings of 3DBODY. TECH 2020-11th International Conference and Exhibition on 3D Body Scanning and Processing Technologies, Online/Virtual, 17-18 November 2020. 2020.

[9] "Face Tracking with ARKit," Apple Inc, accessed 2022 [Online]. Available: https://developer.apple.com/videos/play/tech-talks/601/.

[10] "Structure," Occipital Inc, accessed 2022 [Online]. Available: https://structure.io/.

[11] "Male and female 3D head model 48 X bundle" accessed 2021 [Online]. Available :https://www.3dscanstore.com/3d-head-models/male-retopologised-3d-head-models/male-female-3d-head-model-48xbundle

[12] “Shapeways 3D printing”,. accessed 2022 [Online]. Available : https://www.shapeways.com/wp-content/uploads/2021/05/VisiJet-PXL-Binder-Jetting-Technical-Data-Sheet-TDS-2.pdf

[13] “Sandstone material”,. accessed 2022 [Online]. Available: https://www.shapeways.com/materials/sandstone

[14] "Device Capabilities Required for ARKit“,.accessed 2022 [Online]. Available : https://developer.apple.com/library/archive/documentation/DeviceInformation/Reference/iOSDeviceCompatibility/DeviceCompatibilityMatrix/DeviceCompatibilityMatrix.html

[15] PAULSEN, Rasmus R., JUHL, Kristine Aavild, HASPANG, Thilde Marie, et al. Multi-view consensus CNN for 3D facial landmark placement. In : Asian Conference on Computer Vision. Springer, Cham, 2018. p. 706-719, https://doi.org/10.48550/arXiv.1910.06007

[16] LI, Tianye, BOLKART, Timo, BLACK, Michael J., et al. Learning a model of facial shape and expression from 4D scans. ACM Trans. Graph., 2017, vol. 36, no 6, p. 194:1-194:17.

[17] P. Laurin, D. Béland and J. Borduas, "A fully automated and unsupervised cloud API for the reliable reconstruction of raw 3D surface scans data," in *3D BodyTech*, Lugano, 2019.

[18] ELIASZIW, Michael, YOUNG, S. Lorraine, WOODBURY, M. Gail, *et al.* Statistical methodology for the concurrent assessment of interrater and intrarater reliability: using goniometric measurements as an example. *Physical therapy*, 1994, vol. 74, no 8, p. 777-788.