# Experimental Investigation of the Fit of Face Masks During Speaking Using 3D and 4D Scanning

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## Abstract

Face masks were intensively investigated during the COVID-19 pandemic, but several engineering aspects of their design still remain open. In real world conditions, humans wear masks while speaking or even shouting, which is connected to a larger opening of the mouth. During the motion of the mouth, the position of the jaw changes and therefore the geometry of the lower face. Thus, variations in face shape while speaking should be considered in the evaluation of mask fit.

The objective of this investigation is to evaluate two different scanning methods in terms of analyzing two mask fit indicators, leakage and mask shifting, under dynamic conditions. First, the face of a test person is scanned without and with a mask in two static positions (mouth closed and mouth maximally open) using a 3D scanner. Then, the same test subject is scanned without and with a mask while continuously opening and closing their mouth using the high-speed (4D) MOVE4D scanning system.

The findings of the investigation can be used to decide which scanning method is best suited for which type of mask fit evaluation. Furthermore, more elaborate scanning procedures and analyses for mask fit evaluations using 3D and 4D scanning can be developed based on the presented approaches.

**Keywords:** 3D Scanning, 4D-Body Scanning, Face Masks, Dynamic Mask Fit, Mask Leakage, Mask Shifting, Facial Geometries

## 1. Introduction

Face masks are significant in medicine, construction, and military aviation. They are used either to protect the wearer against dust, pollen, bacteria, and viruses or to supply breathable air and anesthetics. Regardless of their intended use, they can only work properly and comfortably when they fit the wearer's facial geometry. This should hold true not only in static situations with a closed mouth and a motionless face, but also in dynamic situations in which the wearer moves their mouth to speak, shout, etc. Characteristics of a poor mask fit include gaps between the mask perimeter and face, buckling of the mask (especially in the case of an elastic textile mask), a deformed face due to mask pressure, and shifting of the mask, particularly under dynamic conditions.

Several methods exist in the literature for generating individualized masks, i.e. three-dimensional geometries of stiff polymeric masks [1, 2] or two-dimensional sewing patterns of flexible textile masks [3, 4] respectively, based on facial geometry in static and dynamic conditions. Additional methods are needed to validate the fit performance of individually generated face masks by evaluating the aforementioned fit indicators. These methods should facilitate fit evaluation in both static and dynamic conditions.

One existing approach to evaluating mask fit by measuring leakage is to determine the amount of gas that penetrates the gaps between the mask's perimeter and the wearer's face. A test subject wearing the mask stands in a test chamber containing a specific concentration of aerosol or gas and performs designated tasks, such as moving their mouth. Meanwhile, the concentration of the aerosol or gas in the space between the mask and the face is measured and compared to the ambient concentration to determine the amount of gas that penetrates through the mask's leaks. This testing method is standardized in ISO 16900-1 [5] and has been used in several studies under static and dynamic conditions [6, 7]. However, this method merely indicates whether a mask fits well or poorly. It does not specify where around the perimeter the fit is poor. Furthermore, this method is not effective with low-stiffness masks, such as conventional nonwoven masks, because the attached experimental equipment may deform and shift the mask during testing.

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Another method involves virtually donning the mask on the face, with both the mask and the face being rigid, as applied in [1, 8]. First, the geometry of the mask and face were captured separately via 3D scanning. Then, the rigid face and mask were virtually aligned with respect to certain reference points. Measuring the size of the gaps and intersections between the mask and face facilitated the evaluation of leakage and the estimation of pressure between the mask and face at different points, respectively. A program coded in MATLAB performed the alignment of the face and mask as well as the measurement of distances. However, the assumption of mask rigidity is only valid for relatively stiff plastic masks, such as respiratory or pilot masks, but not for flexible textile masks, especially when investigating dynamic conditions, i.e., different facial poses with an open mouth. Assuming that the face is rigid is incorrect as well and a considerable drawback of this method.

The improvement to the aforementioned approach incorporates a virtual fitting simulation using product development software for textile products, such as CLO3D, as in [3, 4]. This method is particularly well-suited to flexible textile masks, the sewing patterns of which are used to virtually sew the masks during the simulation's preprocessing stage. Individual facial geometry is captured via 3D scanning. Kang et al. [4] used the software to calculate the pressure distribution between the face and mask to indicate gaps and wearing comfort. Maher et al. [3] qualitatively observed the mask fit, looking for leakage and buckling, and determined distances between the mask and face of the simulated result for quantitative analysis. However, this method still relies on the assumption that the face is not deformable. Furthermore, even with flexible virtual masks, a realistic dynamic fit analysis is not possible, as existing simulation programs do not offer physically exact fit simulations based on animated avatars (i.e., facial geometries with a smoothly opening mouth).

Another existing approach involves 3D scanning the face and mask while wearing them and subsequently evaluating the scanning data. Goodge et al. [9] scanned a face with and without a mask, with different mouth openings, and before and after speaking, to analyze the fit under dynamic conditions. For each mouth opening length, scans with and without mask were overlaid, and the mask scan's transparency was set to 70% to visually analyze gaps, mask buckling, and deformed facial features due to the mask's pressure. Additionally, they detected mask shift due to mouth movement by overlaying the closed-mouth mask scan before and after speaking, then measuring the distance between certain reference points on the mask in both scans. Schreinemakers et al. [10] limited themselves to capturing one face scan with a mask in a closed-mouth pose. They measured the distance between the mask's edge and the face around the nose to determine leakage. While virtual fit simulations do not allow for realistic fit analysis, especially under dynamic conditions, scanning real wearing trials does not have these limitations. Therefore, the scanning approach is worth to be further investigated and developed.

In this paper, two methods involving 3D and 4D scanning, respectively, are applied for mask fit evaluation. These two methods are qualitatively compared in terms of their ability to detect leakages and mask shifting under dynamic conditions i.e., during mouth movement. The objective of the study is to determine, which method best suits the investigation of which fit indicator.

## 2. Methods

### 2.1. Test person and mask

One test subject (a middle-aged, male European) volunteered for the study. Informal consent was obtained from the participant to use the scan data for this research. The mask was an FFP2 mask made by Baner, model BT-006. All wearing trials were conducted with the same test subject and mask.

### 2.2. 3D-Scanning

*2.2.1 3D-Scanner*

The employed 3D-scanner was the handheld scanner “Leo” made by the company Artec 3D [11]. This scanner applies structured light projection with visible light and triangulation to calculate the location of surface points and an additional RGB camera to capture textures. The scanner's performance data includes a resolution of up to 0.2 mm, an accuracy of up to 0.1 mm, and the ability to merge 22 frames per second in real time to create a spatial 3D scan.

*2.2.2 Scanning procedure*

First, the test person was scanned with his mouth closed. Then, he was scanned a second time with his mouth open. Both scans were performed without a mask. This procedure was then repeated the FFP2 mask. Basically, the procedure followed was the same as in [9] The test subject was asked to adjust the mask to fit his closed mouth as well as possible and to leave it untouched when opening his mouth. For the scans with an open mouth, the test subject had to open his mouth as wide as possible to ensure that the width of the mouth opening was the same in both scans for a valid comparison. Thus, four 3D scans were captured in total. The test subject sat on a chair for each scan to increase stability during scanning. However, small movements of head and face, especially due to breathing, could not be entirely avoided, as one scan took between 20 and 30 seconds. Furthermore, the test subject was asked to wear a black swimming cap to facilitate capturing the entire head. Capturing the entire head simplifies subsequent alignment of the scans because the curvature of the skull provides good support for this task.

*2.2.3 Analysis of scanning data*

Each scan was processed using Artec Studio Professional 18 software from Artec 3D to generate a watertight mesh, which was then exported in OBJ format. The scans were analyzed in the CloudCompare software. Leakages were investigated by comparing respective scans with and without a mask for open and closed mouth states separately. Mask shifting during mouth opening was detected by comparing open- and closed-mouth scans with mask.

First, the software automatically aligned the two scans to be compared after three reference points were set in each scan (see figure 1). These points had to coincide with the corresponding points in the other scan (e.g., A2 with R2). The reference points were placed on the forehead because it is not covered by the mask and does not experience significant shape changes compared to other areas of the face. Peculiar skin features of the test subject were used as markers for the reference points. If the test subject does not have such features, the test procedure can be improved by attaching additional markers to the skin.


*Fig. 1. Preparation of the alignment of two 3D-scans with closed mouth via three reference points.*

After aligning the scans, a cutting plane was placed through the tip of the nose and the chin. This plane was used to generate a cross-section of the aligned scans at the aforementioned vertical facial level to visualize the gaps between the mask and face at the back of the nose and chin, which indicate leakage, as well as the changing position of the mask at the back of the nose, which indicates mask shifting. In all mask scans, the edge of the mask at the back of the nose and chin was marked by a point to simplify the recognition of the mask's edge in the overlaid view (see figure 2).

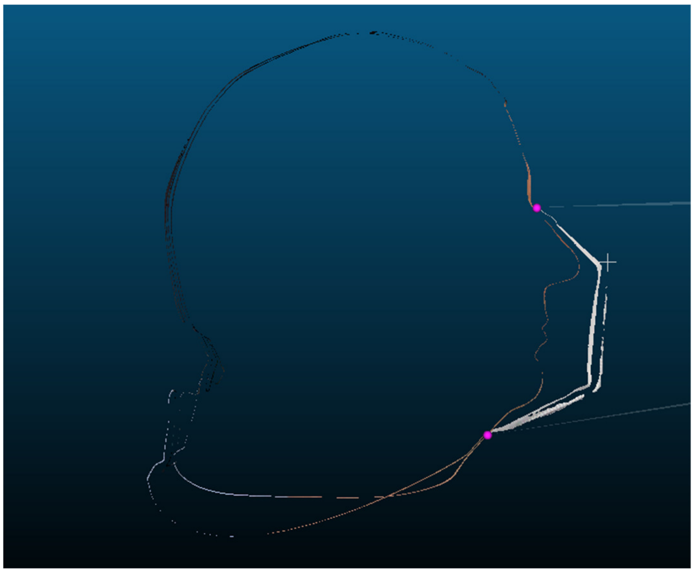


*Fig. 2. Cross-sectional view of two aligned scans to show leakage at nose and chin.*

## 2.3. 4D-Scanning

### *2.3.1 4D-Scanner*

The employed 4D scanner was the MOVE4D scanning system by the Instituto de Biomecanica de Valencia (IBV) [12]. This system consists of twelve modules aligned around the measurement space. Each module uses structured light projection with infrared light and triangulation to calculate the location of surface points and an additional RGB camera to capture textures. Dedicated algorithms merge the frames of all modules into a coherent scan in real time. The scanning system offers a resolution of up to 1 mm, an accuracy of up to 1 mm, and a frame rate of up to 178 frames per second for dynamic scans. The scanner was calibrated just before scanning.

### *2.3.2 Scanning procedure*

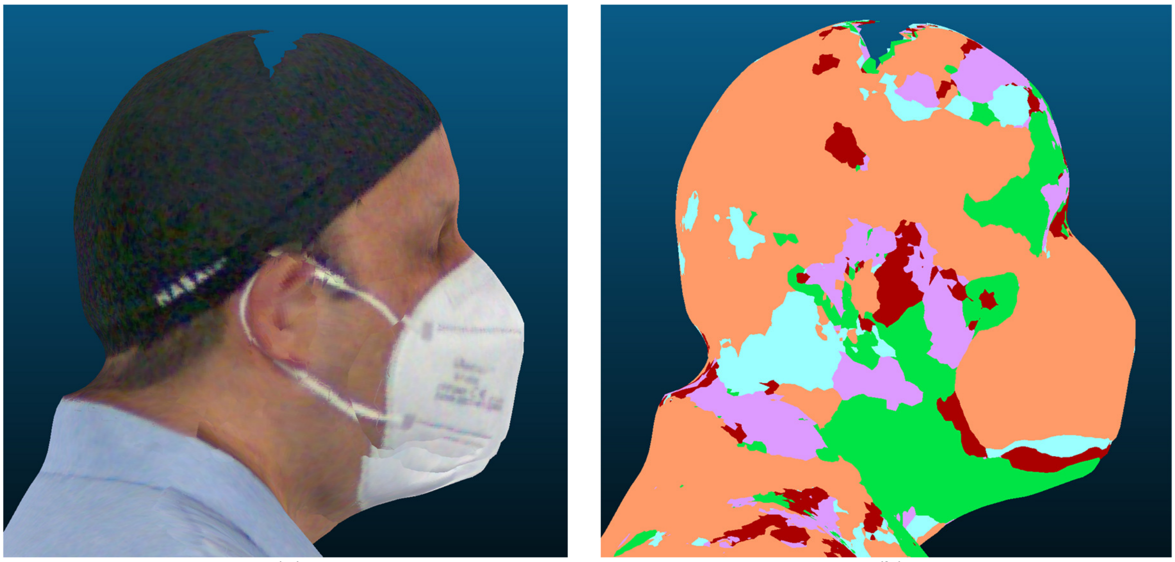
The test subject was scanned twice: once without a mask and once with a mask. In both scans, the subject was instructed to open his mouth as wide as possible and close it again within three seconds after the scan began. The scanning system captured ten frames per second for three seconds at the highest resolution. As with the 3D scans, the test subject sat on a chair and wore a swimming cap.

### *2.3.3 Analysis of scanning data*

The MOVE4D software automatically processed the scans frame by frame. The resulting models were non-watertight and non-homologous, and were exported as OBJ files, with one file per frame. Further analysis of the scanning models was conducted in CloudCompare.

To detect leaks, one frame of the scan without a mask was compared to one frame of the scan with mask. Care was taken to ensure that the mouth opening was as similar as possible in both frames. Since the resolution of the 4D scanning system is lower than that of the 3D scanner, unique features on the test subject's skin could not be detected and used as markers for alignment. Therefore, the frames were manually aligned. For future investigations, the use of attached markers on the forehead is therefore highly recommended.

Mask shifting was evaluated by aligning five frames of the mask scan with different mouth openings (see figure 3). The advantage of 4D scanning over 3D scanning is that the frames of the same 4D scan can be aligned straight in software like CloudCompare without adding reference points because all frames are captured in the same coordinate system. Therefore, given that the head was kept as steady as possible during scanning, the head is always in the same position in the software's coordinate system upon loading.



(a) (b)

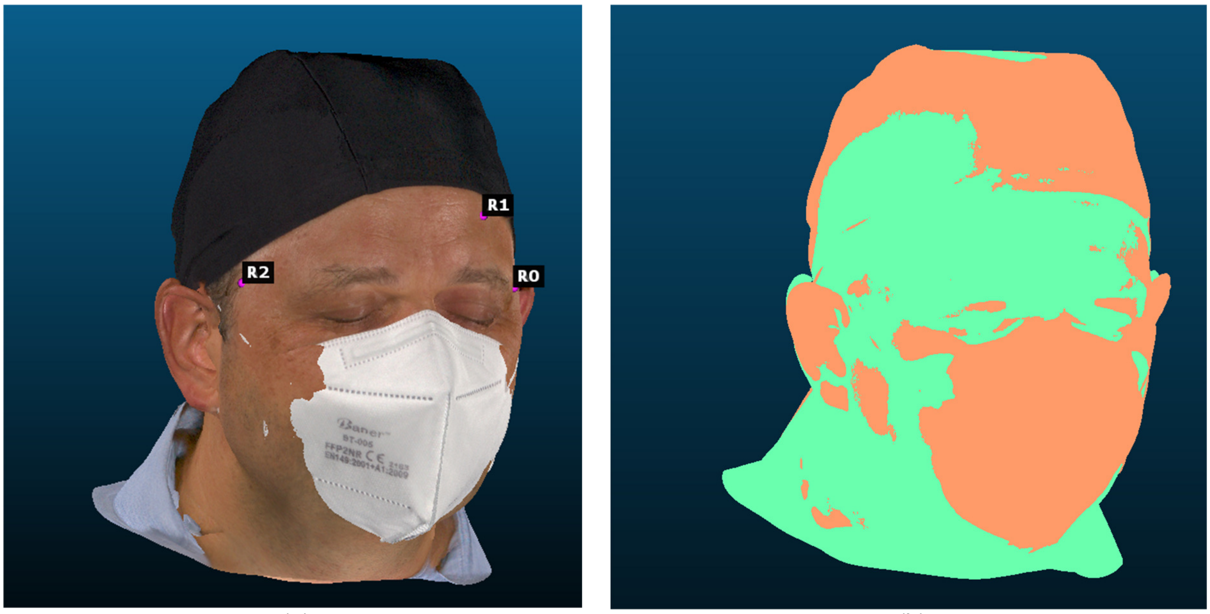
*Fig. 3. Five frames of the 4D mask scan aligned to evaluate mask shift with textures (a) and with different colors for each frame (b).*

After alignment, all scans were treated the same way as the 3D scans were. This involved placing a cross-sectional plane at the level of the nose and chin and marking the edges of the mask at these points.

## 3. Results and discussion

### 3.1. Analysis of Leakages

Aligning the 3D scans with and without a mask at the same mouth opening (see figure 4) revealed that the mask applied pressure to certain areas of the face, deforming it in those areas. In the overlaid scans, the mask scan is immersed into the unmasked scan in these areas, especially the cheeks. The magnitude of facial deformation and scan overlap increases as the mouth opens wider, since larger openings trigger larger pressure from the mask on the face. The same effect was observed in the 4D scans. However, this phenomenon does not affect the reliable visual evaluation of leaks, since an overlapping area merely indicates the absence of a gap, as the corresponding pressure requires contact.



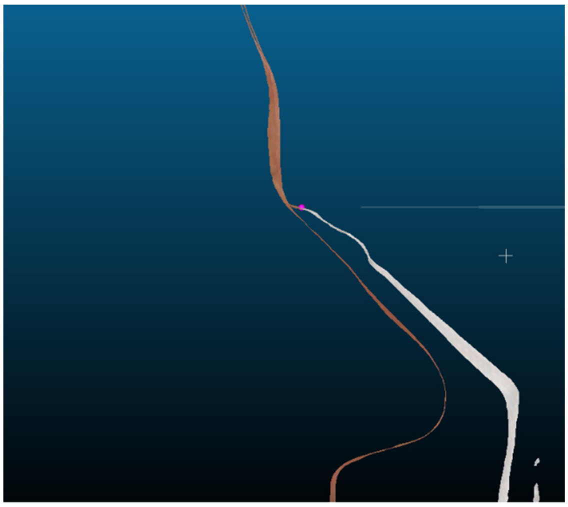

(a) (b)

*Fig. 4. Aligned 3D-scans with and without mask, both with mouth closed, with textures (a) and colored in green (without mask) and red (with mask) respectively (b).*

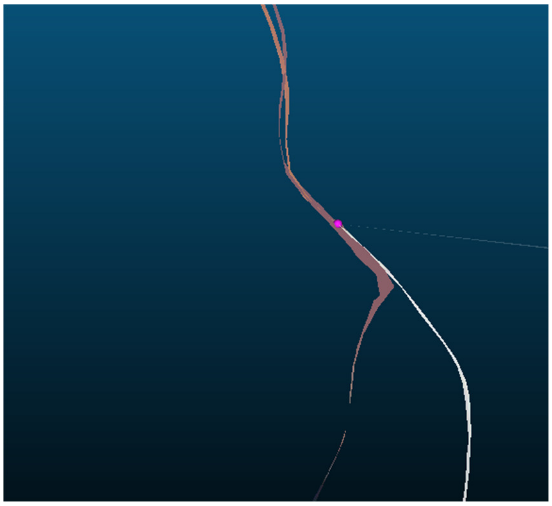
As for the scanning data analysis for evaluating leakages, the 4D scanning approach was more difficult to conduct. Determining two frames, one from the scan without a mask and one from the scan with a mask, with nearly the same mouth opening width and aligning them properly was time-consuming manual work. Since it was difficult to make sure that the test subject begins to open his mouth at the same time and with the same velocity in both 4D scans, it was not possible to identify two frames with the same mouth opening merely by looking at the same position within the frame sequence. Furthermore, there is no guarantee that two frames with nearly the same mouth opening width exist after scanning at all. The only way to increase the probability of finding such a match is to increase the number of frames per second in the 4D scans, but this significantly increases the time required for automatic data processing for the mesh generation.

On the other hand, the 3D scanning method enabled the reproducible scanning of static mouth openings, which simplified the subsequent analysis of the scanning data. However, scanning many different static mouth openings with 3D technology took more time and is generally more difficult to realize than scanning equivalent mouth motions with 4D technology (approx. 15 min more time per frame for 3D scanning than for 4D scanning). To investigate additional reproducible mouth openings within the range of a closed mouth to a fully open mouth using static 3D scans, the test subject should be instructed to bite on an object of a certain size during scanning without a mask. The same object could then be used for the mask scan, ensuring an equal mouth opening width in both scans. However, this approach requires the test subject to remove the mask to switch between two different mouth opening poses, since the object to be bitten has to be changed. This may alter the fit of the mask in the second open-mouth pose compared to when the mask was worn continuously during the opening motion.

A comparison of the visual results of the prescribed scanning data analyses (see figure 5) reveals that the higher resolution of the employed 3D scanner yielded a significantly more realistic image of the mask fit and leakages (a) than the 4D scan (b), which, due to its lower resolution, was merely capable of approximating the realistic geometries. Therefore, it is recommended to employ a scanner with a resolution of approximately 0.2 mm instead of a scanner with a resolution of 1 mm for the purpose of leakage evaluation.



*(a)*



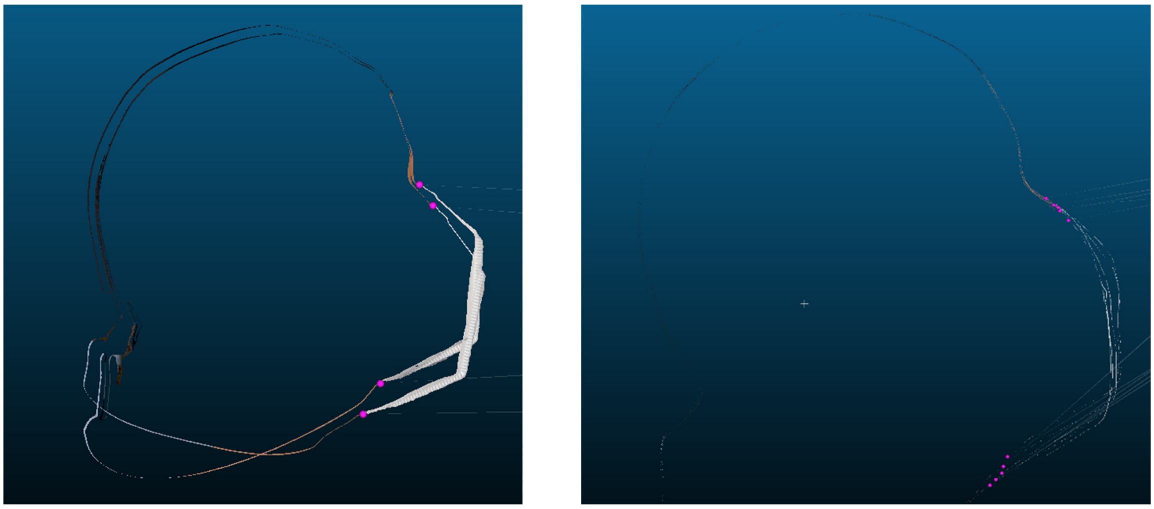
*(b)*

*Fig. 5. Cross-sectional view of aligned mask scans after 3D scanning (a) and 4D scanning (b) for evaluation of leakages.*

### 3.2. Analysis of mask shifting

The effort required for the capturing and analysis of the scanning data for the mask shifting evaluation was found to be considerably less with the 4D scanning approach in comparison to the 3D scanning approach (approx. 30 min for 4D scanning with five frames including 20 min of automatic data processing for mesh generation compared to approx. 50 min for 3D scanning with only two frames). This is due to the fact that the previously mentioned capturing of all frames of the 4D scan in the same coordinate system facilitates the straightforward and accurate alignment of scans within the software. In contrast, 3D scans require the initial marking of reference points.

The visual results of the mask shifting evaluation (see figure 6) further indicate the superior quality of the 3D scans (a). However, the inferior quality of the 4D scans (b) is sufficient to clearly display mask shifting during mouth motion, as the edge of the mask is always well-recognizable. Considering, that the scanning and analyzing effort is significantly lower, the application of 4D scanning instead of 3D scanning for the evaluation of mask shifting is recommended.



*(a)* *(b)*

*Fig. 6. Cross-sectional view of aligned mask scans after 3D-scanning (a) and 4D-Scanning (b) for evaluation of mask shifting.*

## 3. Conclusion

The objective of the investigation was to compare two different scanning approaches with respect to the evaluation of two indicators of mask fit, leakage and mask shifting, under dynamic conditions. The 4D scanning approach was determined to be more convenient and time-efficient than the 3D scanning approach with respect to data capturing. With regard to the leakage evaluation, however, 3D scanning proved to be more advantageous in terms of data analysis, specifically with regard to the matching of two scans with equal mouth opening width and the correct alignment of the scans. Furthermore, the 3D scanner, with its resolution of 0.2 mm, was found to be the optimal choice for capturing leakages with a high degree of realism and preferred over the 4D scanning system with a lower resolution of 1 mm. In terms of the evaluation of mask shifting, the scanning data analysis could be conducted with minimal effort using the frames of the 4D scans. Additionally, the inferior quality of the 4D scans in comparison to the 3D scans was not decisive for the identification of the mask shift. Therefore, the 4D scanning approach that has been prescribed can be recommended for the mask shifting analysis.

Both of these methods can be used for future, more detailed studies. Adding more cross-sectional planes parallel to the nose-chin plane would facilitate a more globalized analysis. Additionally, measuring gaps and mask shifts, as applied in [9, 10], would make the analyses more quantitative.

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