**Author's response to reviews**

**Title:** Simultaneous, radiation-free registration of the dentoalveolar position and the face by combining 3D photography with a portable scanner and impression-taking

**Authors:**

Lucas Ritschl (lucas.ritschl@tum.de)

Klaus-Dietrich Wolff (klaus-dietrich.wolff@tum.de)

Pia Erben (pia.erben@tum.de)

Florian Grill (florian.grill@tum.de)

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Reviewer reports and detailed response to the comments

Reviewer #1: Language review - excellent. However, in the 'Limitations', it is better to avoid beginning a sentence with 'but'. Try 'however' instead

Reply: Many thanks for reviewing the language of our manuscript. We have changed 'but' to 'however'.

Reviewer #2: The authors state: "Such approaches are lacking in recent literature" (line 23): The concept of matching intraoral surfaces with a facial scan is not new. One reference to a similar publication was given by the authors themselves (Bechtold et al. 2012). In fact, different techniques with and without ionising radiation have already been subject to a review (and clinical study) in 2018 by Managno C et al. (Combining Intraoral Scans, Cone Beam Computed Tomography and Face Scans: The Virtual Patient. J Craniofac Surg 2018; 29: 2241-2246).

Reply: We thank the reviewer very much for this elaborate review and many suggestions for enriching our reference list, and to give us the opportunity to clarify the intention of our study. We have inserted the presented literature including the review of Managno et al. who summarizes various studies that combine x-ray based imaging with 3D facial scans.

The Introduction-Section has therefore been supplemented with the sentence: „An overview about various investigations was provided by Mangano and colleagues [1-3].”

With hollow spherical marks on an intraoral wax rim (e. g. Schweiger J et al.: Virtual evaluation for CAD-CAM-fabricated complete dentures. J Prosthet Dent 2017; 117: 28-33) or visible
dental or prosthodontic surfaces (e. g. Hassan B et al.: A digital approach integrating facial scanning in a CAD-CAM workflow for complete-mouth implant-supported rehabilitation of patients with edentulism: A pilot clinical study. J Prosthet Dent 2017; 117: 486-492), matching intraoral an facial 3D-Surfaces has also been performed before.

Reply: Thank you for pointing out these two studies to us. We have added them in our Introduction Section as a possible workflow to create CAD/CAM-assisted complete dentures. The main difference to our investigation is, that edentulous jaws and a model of dentures were registered with facial scans by matching, whereas no definite (CAD/CAM) registrations were used – which however is a main advantage of our study. The matching in the studies mentioned above is limited to the visible intraoral part that is held back by the soft-tissue retractors.

The following wording has been added: „In cases of an edentulous jaw Schweiger et al. as well as Hassan et al. presented a virtual workflow for complete dentures for which also facial scans were used. Their workflow aligns the digitalized dental arches according to the facial scan and provides valuable information to evaluate the tooth arrangements, however, without a definite intra-extraoral registration [20, 21].”

A Scanbody similar to the one the authors used with spherical marks has been described by Bechtold in 2012 (see above) and patented in 2017/2018 by K. Tegtmeyer (who also used a mobile scanner and a smartphone). (https://patents.google.com/patent/WO2018172263A1/de)

Reply: Many thanks for providing the source of this patent. To credit the international patent, we have added it in our reference list. Our geometries, that have been designed independently of the mentioned patent, have less contact to the lips and are in our opinion easier to be transferred to the clinical practice. We have changed the Discussion-Section accordingly to: “The idea of digital facebows that combine intra- extraoral registrations using spherical geometries have been described and patented before [6]. Our geometries, that have been designed independently of the mentioned patent, have less contact to the lips and are in our opinion easier transferred to the clinical setting.”

Using spherical target marks to match scanned surfaces is also a well-known procedure. "Spherical targets are widely used because of their unique benefit that they can be viewed from any angle and always provide a homogeneous reference surface” (Brazeal R: [7]. https://www.researchgate.net/publication/265014634_LOW_COST_SPHERICAL_REGISTRATION_TARGETS_FOR_TERRESTRIAL_LASER_SCANNING; 2013), further explanation of algorithms and a study on the impact of target mark geometry on accuracy can be found in Elkhrachy, I and Niemeier, W: Fitting sphere targets and their impact on data registration accuracy for terrestrial laser scanner. https://www.researchgate.net/publication/270565358_Fitting_sphere_targets_and_their_impact_on_data_registration_accuracy_for_Terrestrial_laser_scanner

Reply: Thank you for pointing out the topic of spherical geometries to us. The benefit of spherical geometries in our study is not that they can be detected from any angle- since the face
must be scanned from many angles anyway in order to capture the nose from both sides, but the scanner can seemingly detect spherical geometries far easier and more precisely due to its scanning algorithm. In case of edges it tends to make them round as shown in our data with the RMSE analysis. Further, the spherical geometry was not intended to be presented as novel nor intended to claim a patent, however, it was to determine in a preliminary examination, which kind of geometry works better for exactly our scanner used in our clinical practice. By that, we have described, that once both geometries have been scanned, the alignment shows no differences in RMSE analysis, despite one might think that a geometry with edges can be aligned more precisely (edge to edge alignment as perceived by the human eye). The scanner however, works with both geometries, once scanned.

To clarify this in our manuscript we have changed the wording in the Methods- and Discussion-Section to:

“As a preliminary investigation concerning the scanner used, we intended to evaluate the scannability of two kinds of extraoral geometries which were then compared:…”

And

“Furthermore, a cross-like geometry seems to be more suitable for the alignment due to definite edges which can be used for reference marker positioning. However, our analysis showed, that the spherical geometry is detected better by this scanner used in our clinical practice due to the technical scanning algorithm – the cross was also fully scanned but the edges seemed to be radiused. Since the scanner needs always a swing e.g. for scanning the nose completely, the advantages of the detection of a spherical geometry compared to an edged geometry are pushed into the background. Once scanned, there were no statistically significant differences in RMSE analysis between the two kinds of geometries. “

In addition, we have refined the description of our scanner that it is a blue-light-LED scanner in the Abstract and in the Methods-Section.

So the radiation-free data acquisition in dentistry, the use of an extraoral scanning target fixed to the dental arches, the advantages of a spherical target over other geometries, the matching procedure for the surfaces and the use of a portable surface scanner have all been studied and published before. I would therefore strongly recommend pointing out more clearly what was essentially new in the manuscript. As I understand it, the main difference to the procedure Bechtold described is the reduction of ten to six steps. The authors forewent an additional facial scan without the target marks in place, Bechtold et al. performed this second scan to get a facial surface with lips closed and undisturbed by the device. Bechtold also used plaster models and scanned them with the target marks and without and in occlusion (three steps), whereas the authors used an impression scan with normal inversion.

Reply: We agree that there have been previous investigations on this topic. However, our study presents an addition and facilitation to existing literature and provides an easy-to-use digital basis for downstream applications. Our study shows an actual way from a theoretical concept to
clinical practicability. The presented workflow allows the superimposition of any facial expressions, as well, as long as the selected reference points are visible, such as medial canthus, soft tissue nasion, glabella or pogonium.

To point out the particularity of our study, we have adapted our Discussion-Section by adding the following:

“In summary, the study presents an optimization of our chair-side 3D scanner which can be transported and used anywhere as compared to a stationary system. Despite having the advantage of a hand-held device there are no cutbacks on a high scanning resolution as in cases of other mobile devices such as tablets or smartphones. We show an easy-to-replicate six-step workflow that can be used for digital planning or pre- and postinterventional documentation which is intuitively accessible.”

Therefore, as a consequence of the reduction of steps, there is also a reduction of information.

Reply: We thank the reviewer for pointing this out. We have added this thought into our Discussion-Section. In our study, we describe a possible workflow for pre- and postinterventional documentation. In our opinion, the accuracy for this indication is sufficient as our now additional analysis of variance (ten repetitions of the complete alignment) shows. Moreover, and more importantly, the likeliness to actually perform this kind of three-dimensional documentation in the clinical daily routine is higher when the workflow is easier.

The wording in the Discussion-Section has been changed to:

“… and showed a low variance of alignments after a ten-fold workflow repetition. The reduction of information when only performing six steps instead of ten seems to have only minor or even no impact.”

I would also recommend revising the text with respect to the instructions for authors, especially the references list, e.g:

Line 283: The Author "A. Gerber" should be named correctly.

Line 344: The Journal of Orofacial orthopedics/Fortschritte der Kieferorthopädie is abbreviated J. o. O. O. d. K. in the manuscript and placed between the authors. This should be changed according to the Instructions for authors.

Line 351: The title of the journal (Behaviour research methods) is missing. Same is true for line 353.
Reviewer #3:

The authors present a study in which they evaluate a method for integrating 3D models of the dentoalveolar arch into 3D facial models. The data are acquired by a portable 3D scanner. In parallel, an impression of the maxillary dental arch is taken with one of two different reference targets ("scan bodies") attached to the impression tray. Subsequently, the tray with the attached target is rescanned extraorally. The scanned impression is then registered by matching the two data sets of the target. The accuracy of the procedure is estimated by measuring the RMSE differences between the matched data sets.

Comments:

The manuscript is generally well written with adequate illustrations. However, it is not completely clear what the novel aspects of the investigation are. The whole procedure is quite straightforward and similar to earlier work presented by, e.g., Bechthold et al. (2012) and others. The main difference in relation to the mentioned work appears to be the use of a portable scanner instead of a stationary one.

Reply: We thank the reviewer for the comment. To point out the particularity of our study, we have adapted our Discussion-Section by adding the following:

“In summary, the study presents an optimization of our chair-side 3D scanner which can be transported and used anywhere as compared to a stationary system. Despite having the advantage of a hand-held device there are no cutbacks on a high scanning resolution as in cases of other mobile devices such as tablets or smartphones. We show an easy-to-replicate six-step workflow that can be used for digital planning or pre- and postinterventional documentation which is intuitively accessible.”

Furthermore, the study lacks an estimation of the accuracy of the jaw model as it is transferred to the intraoral position. In summary, the authors present only a comparison of the accuracy of the registration of the two reference targets, one of which is obviously unsuitable given the limited resolution of the scanner.

Before a publication can be considered, I would therefore recommend the following additions in order to achieve a benefit for the reader: 1. Considering the intended application, an estimation of the required accuracy of the inserted models should be made. 2. At least the precision (i.e., repeatability) of the intraorally positioned models should be determined. This could be done, for
example, by repeating the procedure sufficiently often on a test person with subsequent
evaluation of the distance matrix to obtain a measure of the variance of the results.

Reply: We thank the reviewer for his valuable comments. We agree that an investigation of the
variance of the workflow might be in the interest of the reader and represents a valuable addition
to our study. We have therefore made ten repetitions of the digital workflow with a test person
and have performed a RMSE analysis (see Method and Results Sections and below).

Furthermore, we have added a section to our Discussion addressing the accuracy of digital three-
dimensional workflows and compared them to our own findings. Please find our wording now
updated to the following:

In the Methods-Section:

“An analysis of the variance of a tenfold repetition of the digital workflow has been performed.”

In the Results- Section:

“The tenfold repetition of the virtual alignment workflow showed a mean RMSE of 0.27 (range:
0.17 – 0.40) with a standard deviation of 0.078 and a variance of 0.006.”

And in the Discussion-Section:

“Lin et al. and Jayaratne et al. compared the accuracy of low-dose cone beam CT scan protocols
with the 3dMD system and obtained an RMSE between 0.74 ±0.24 and 1.8 ± 0.4 mm. The
precision of other stationary 3D camera systems is reported to be good with the mean absolute
differences for the VECTRA system lying within 1.2 mm and less than 1 mm by using 3dMD. These
reported results are more precise than a deviation of 2 mm. RMSE values larger than 2
mm are considered unreliable according to the literature. Our tenfold repetition of alignment and
the consecutive analysis of RMSE of the superimposed models showed a mean of 0.27 and a
variance of 0.006 For documentation and illustration for the patient, this deviation is clinically
negligible. Virtual surgery planning (VSP) is reported to be feasible, reliable and accurate. But
nevertheless, difference between virtual plan and postoperative result still ranges between 1-2
mm or up to ± 12.5° in mandibular reconstructions using the free fibula flap and in VSP-
orthognathic surgery.

Nevertheless, studies comparing 3D photos compare only the “theoretical truth” with all the
inaccuracies of the used systems. Further, no technique enables a precise simulation and
prediction of the postoperative result, yet. Within the reported and known limitations we
therefore think, that our results are clinically acceptable and relevant.”