

Registration-Free Workflow for Electromagnetic and Optical Navigation in Orbital and Craniofacial Surgery

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TITLE PAGE

REGISTRATION-FREE WORKFLOW FOR ELECTROMAGNETIC AND OPTICAL NAVIGATION IN ORBITAL AND CRANIOFACIAL SURGERY

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ABSTRACT

The accuracy of intra-operative navigation is largely dependent on the intra-operative registration procedure. Next to accuracy, important factors to consider for the registration procedure are invasiveness, time consumption, logistical demands, user-dependency, compatibility and radiation exposure. In this study, a workflow is presented that eliminates the need for a registration procedure altogether: registration-free navigation. In the workflow, the maxillary dental model is fused to the pre-operative imaging data using commercially available virtual planning software. A virtual Dynamic Reference Frame on a splint is designed on the patient's fused maxillary dentition: during surgery, the splint containing the reference frame is positioned on the patient's dentition. This alleviates the need for any registration procedure, since the position of the reference frame is known from the design. The accuracy of the workflow was evaluated in a cadaver set-up, and compared to bone-anchored fiducial, virtual splint and surface-based registration. The results showed that accuracy of the workflow was greatly dependent on tracking technique used: the workflow was the most accurate with electromagnetic tracking, but the least accurate with optical tracking. Although this method offers a time-efficient, non-invasive, radiation-free automatic alternative for registration, clinical implementation is hampered by the unexplained differences in accuracy between tracking techniques.

TEXT

INTRODUCTION

Accurate intra-operative registration is the cornerstone to acquire reliable positional information in intra-operative navigation¹⁻⁹. The ideal registration method would be non-invasive, little time consuming, not logistically challenging, automatic and thus not user dependent, usable in every patient, compatible with each tracking technique (optical and electromagnetic (EM)), not exposing the patient to additional radiation and, most of all, accurate.

Currently, several registration concepts exist in craniofacial surgery: fiducial markers, splints, or a combination of the two may be used in point-based registration^{3,5,7,10,11}. Surface-based registration may be accomplished through touch or laser surface scanning. Next to specific drawbacks regarding accuracy, invasiveness and usability, each of these methods requires user interaction. The result of the registration process will be user dependent to some degree. Automatic Image Registration overcomes the user-dependency issue: intra-operative imaging is acquired with the Dynamic Reference Frame (DRF) in place^{7,10,12}. If a virtual planning is made on the pre-operative image set, image fusion allows integration of the intra-operative registration scan in the virtual surgical planning. While the user-dependency drawback is eliminated, issues regarding radiation exposure and extended operation time remain.

In this study, a registration-free dental splint-based method is proposed that eliminates user dependency and does not require acquisition of additional intra-operative imaging. The methodology of registration-free navigation is outlined and the accuracy is compared to bone-anchored maxillary fiducials (optical and EM) and surface-based registration (EM).

METHODS

Five dentulous cadaver heads were obtained through the body donation program from the Department of Medical Biology, Section Clinical Anatomy and Embryology of the Amsterdam UMC (location AMC). The bodies from which the samples were taken were donated to science in accordance with Dutch legislation and the regulations of the medical ethical committee of the Amsterdam UMC. The experimental protocol was approved by the review committee of Medical Biology, Section Clinical Anatomy and Embryology (ref. 2018-087). All methods were performed in accordance with the relevant guidelines and regulations. The dental status (maxilla) of the cadavers is shown in Table 1. The fixated cadaver heads were equipped with five titanium screws (1.5 x 5.0 mm maxDrive screws, KLS Martin, Tuttlingen, Germany) on the maxilla for bone-anchored fiducial registration, and fourteen Poly-Ether-Ether-Ketone (PEEK) Allen screws to serve as target positions at the following anatomical landmarks: orbital rim (bilaterally), zygomatic prominence (bilaterally), lateral orbital wall (bilaterally), porion (bilaterally), nasion, frontal bone (bilaterally), cranium and occipital bone (bilaterally). A Computed Tomography (CT) scan was acquired and imported in the Origin/Brainlab environment (iPlan version 3.0.6, Brainlab AG, Munich, Germany), a digital landmark was indicated on the Allen screw positions. The coordinates of these landmarks were used as the ground truth in the Target Registration Error (TRE) quantification. The CT scan was also imported in IPS CaseDesigner (version 1.4, KLS Martin, Tuttlingen, Germany), where an intra-oral scan of the maxillary dentition (TRIOS 3 intraoral scanner, 3Shape, Copenhagen, Denmark) was fused to the maxillary dentition of the CT scan¹³. The experimental set-up is visualized in *Figure 1*.

[TABLE 1]

[FIGURE 1]

Mathematically, the registration procedure determines the transformation of the Dynamic Reference Frame from its reference position to the position in the patient image volume: T_{reg} . The instrument's position in the operation room (OR) could be expressed as a position relative to the DRF. Through transformation with the aforementioned registration transformation, the location and orientation of the instrument in the image volume are calculated and visualized. Theoretically, T_{reg} could be determined pre-operatively if the position of the DRF in the image volume were known, thus rendering any intra-operative registration mute. To accomplish this, the fused dental model in IPS was exported as a stereolithographic model (stl). In Blender (version 2.81, Blender Foundation, Amsterdam, the Netherlands), the maxillary dental model was imported and a splint fitting the dentition was designed. An offset of 0.1 mm for the dental model was used to ensure proper splint fit. Two augmentations of the splint were implemented: one to equip the splint with reflective markers resembling the Skull Reference Array (Brainlab AG, Munich, Germany) for optical navigation, and one resembling the EM Reference Holder (Brainlab AG, Munich, Germany). Design of the splint took approximately 15-20 minutes. An outline of the registration-free workflow and a visualization of the designs are provided in *Figure 2*.

[FIGURE 2]

The reference positions of the optical and EM DRF were provided by the manufacturer; the transformation of the DRF to the position on the splint could be calculated in the design environment ($T_{DRF(IPS)}$). A transformation between the IPS and Brainlab image coordinate system ($T_{IPS}^{Brainlab}$) was necessary to obtain the corresponding position in the Brainlab environment ($T_{DRF(Brainlab)}$). The formula for $T_{IPS}^{Brainlab}$ is provided below. The ImagePositionPatient (IPP) can be extracted from the DICOM header information. When the splint is positioned during surgery, $T_{DRF(Brainlab)}$ would represent the DRF's position in the patient image volume and could thus be used as T_{reg} : the need for intra-operative registration would be obsolete.

$$T_{IPS}^{Brainlab} = \begin{bmatrix} -1 & 0 & 0 & -X_{IPP} \\ 0 & -1 & 0 & -Y_{IPP} \\ 0 & 0 & 1 & Z_{IPP} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Currently, the navigation software is not equipped with a functionality to set T_{reg} pre-operatively: a registration procedure is mandatory to use the navigation hardware. To circumvent this, a pre-registration procedure was performed, which was later corrected by back-transformation of the acquired data with this pre-registration T_{reg} and transforming the data with the designed registration $T_{DRF(Brainlab)}$. The splint corresponding to the used tracking technique was positioned and secured using power chains. To assess the Target Registration Error in registration-free navigation, five repetitions were performed by each observer (RS, FB) for each tracking technique (optical, EM). The navigation instrument was positioned at the Allen screws and the coordinates

were stored through the Acquire-functionality. The splint was repositioned after each repetition, since this is the primary act that determines the measurement outcome.

The TRE assessment for bone-anchored maxillary screws and soft-tissue registration were performed in a similar fashion: each observer (RS, FB) performed five repetitions of registration with bone-anchored fiducials with optical navigation, five repetitions of bone-anchored fiducials with electromagnetic navigation and five repetitions for soft-tissue registration with electromagnetic navigation. The Kick navigation system (Brainlab AG, Munich, Germany) was used for all measurements, since this system is compatible with optical and electromagnetic tracking. The Craniomaxillofacial Brainlab module (CMF) was used for optical navigation; soft-tissue registration was not available in this module. The ENT module was used for all EM measurements; for soft-tissue registration, the instructions provided by the system were followed.

The data for each measurement session were stored in DICOM format and exported from the navigation system. In Matlab (version 2019b, the MathWorks Inc., Natick, MA, USA), the acquired landmarks were extracted from the DICOM data. The recalculation of the coordinates, through the previously described back-transformation and transformation, was performed. The Euclidean distance between the resulting coordinate and the target coordinate was calculated (TRE); the Euclidean distances were exported as comma-separated values (csv). A linear mixed model incorporating all measurements was generated in R^{14,15}. The fixed effects were tracking technique, registration method and target distance, as well as their interactions; target distance was again recalculated to the distance of a target to the mean infraorbital rim position (to provide a meaningful intercept).

RESULTS

1396 measurements were obtained using registration-free navigation, 4 (0.3%) were missing. In total, 3496 data points are included in the results. In *Figure 3*, histograms and kernel density estimates for the TRE and \sqrt{TRE} are provided for registration-free navigation and in *Figure 4* the histograms and kernel density estimates for bone-anchored fiducials and soft-tissue registration. The \sqrt{TRE} data distributions most closely represent a normal distribution. In Table 1, the fixed effect estimate output of the complete linear mixed model is provided. The data are recalculated to an intercept value (at the level of the infraorbital rim) and a slope value (increase \sqrt{TRE} per mm distance from the intercept) for each combination of registration method and tracking technique in Table 2. In *Figure 5*, \sqrt{TRE} is plotted against target distance for all combinations, by using the acquired slope and intercept values.

[FIGURE 3]

[FIGURE 4]

[TABLE 2]

[TABLE 3]

The plot in *Figure 5* demonstrates that the EM registration-free approach outperforms all other registration approaches, but the optical registration-free approach is outperformed by bone-

anchored fiducial optical registration and all EM registration approaches. In *Figure 6*, combined kernel density estimate and scatter plots are given for the registration-free data. The regression lines from *Figure 5* are superimposed on the scatter plots. For the EM registration-free measurements, 11% of TRE measurements was >2mm, for the optical measurements this was 41% (compared to 27% for optical bone-anchored fiducials, 15% for electromagnetic bone-anchored fiducials and 17% for electromagnetic soft-tissue registration).

[FIGURE 5]

[FIGURE 6]

DISCUSSION

A novel registration-free approach for orbitocraniofacial intra-operative navigation was introduced in this study. The target accuracy of the method was evaluated and compared to the accuracy of bone-anchored fiducial registration and surface-based registration. The registration-free approach yielded excellent results compared to conventional approaches with EM tracking, but the results in the optical tracking setting were unfavorable to any of the alternative intra-operative registration methods. This large deviation between the tracking methods makes the results difficult to interpret. The deviation in results between both tracking techniques is unexpected. Two differences can be distinguished between the registration-free procedure for EM and optical navigation: one regarding design and one regarding pre-registration procedure. These differences and their possible effect on the registration accuracy will be detailed below, but neither provides a solid explanation for the difference or its magnitude.

The attachment of the Dynamic Reference Frame on the registration splint is different between the optical and electromagnetic setting. The EM tracker is positioned within a holder on the palatal side of the splint; the holder is attached to the molar region on either side. The optical tracker is not attached to the design but is incorporated in it: the reflective markers are attached to three arms extending on the mesial side of the central incisors. While direct incorporation in the design should be less error-prone, the optical design may suffer from reduced stiffness in the material because of the extensions' length, which might have affected the true position of the reflective marker spheres and thus the DRF as a whole. Venosta et al. noticed the influence of material stiffness on registration accuracy in their extended splint design⁵. The DRF splint was designed bearing maximum bending resistance in mind: a rounded edge design was chosen for the extensions over a cubic one for precisely this reason. The location of the DRF in relation to the dentition might also have influenced positioning accuracy. After securing the splint, positional deviation between the DRF in EM may be mostly due to differences in splint fit on the molars, while a positional deviation in the optical tracker may occur because of a difference in fit between the molar region and the incisors. Ye et al. have investigated splint fit, and in their results a difference in splint fit between the incisor region and the molars can be seen¹⁶. However, this difference is only minimal and the recommended offset of 0.1 mm, which resulted in the smallest fit deviation, was used in this study.

The second difference was in the mandatory pre-registration (performed to meet the requirements of the navigation system, but corrected for by the back-transformation). In the EM measurements, the DRF was positioned on the splint and the splint was positioned and secured on the cadaver's dentition. The pre-registration was performed using surface-based matching. The result of this registration was corrected for in the final results, as outlined in the Methods-section. In the optical navigation setting, the pre-registration was performed while a Dynamic Reference Skull Array was

fixated to the cadaver's skull (skull-based DRF); point-based fiducial registration was used to determine the position of the reference array. The skull-based DRF was subsequently removed and replaced by the splint-borne DRF (DRF on the maxillary splint). This workflow was chosen because surface-based matching was not available, and the position of the splint DRF would interfere with the registration process on the bone-anchored fiducials. The landmarks collected with the Acquire-functionality were outside the image volume assigned in the DICOM information. The pre-registration transformation, and any error associated with it, was again corrected, so this should not have had any influence on the registration-free TRE measurements. The orientation difference between the skull-fixated and splint-borne dynamic reference frames might give rise to some technical error in measuring the positions of the reflective marker spheres by the optical camera, but this error is not expected to be in the order of magnitude of the TRE difference.

Several studies have proposed designs of a Dynamic Reference Frame supported by a splint^{17,18,27,28,19-26}. This position of the Dynamic Reference Frame may be less invasive than fixation on the patient's cranium²⁹. Registration outside the patient has been proposed, both with a fiducial-based^{17-20,22-24} and automatic method²⁵⁻²⁸. The fiducial-based registration is possible if the design has both registration fiducials and the DRF attached to the splint. The splint and the fiducials need to be positioned in the patient's mouth during acquisition of the scan; the DRF may be rigidly fixated to the splint or attached later. The relationship between the fiducials and the DRF will not change, so registration can be performed before the splint is positioned in the patient's mouth. A prerequisite is that the splint position does not differ between image acquisition and surgical setting. This workflow is still susceptible to Fiducial Localization Errors in the image volume and physical space, since a registration still needs to be performed⁴. In the automatic registration methods proposed, the DRF is connected to the splint and present in the image volume, or a unique connection between splint and DRF is designed. The position of the DRF in the image volume, and thus T_{reg} , may be determined on the pre-operative scan. This method is similar to the registration process described here, but requires image acquisition with the splint in position, which frequently leads to acquisition of a second scan and additional radiation exposure for the patient.

Intra-operative Automatic Image Registration suffers from the same drawback. In this workflow, the Dynamic Reference Frame is fixated intra-operatively, and during acquisition of a Cone-Beam CT (CBCT) the DRF is tracked with the optical camera^{7,10,12,30}. This method yields an accurate registration, even if low-dose scan protocols are used, but may lead to an increase in operation time and pose logistical challenges intra-operatively^{10,12}. A compatible intra-operative scanner is required, and currently, this method is only available for optical tracking. Other methods of user-independent registration have been proposed: a stereotactic mask, which uses active LEDs, or 3D stereophotogrammetry to capture the soft-tissue of the patient with the DRF in place^{9,31-33}. The stereotactic mask is attached to the patient's face and is used for both registration and tracking, which means that the mask has to stay attached during the complete procedure. This may limit its application in reconstructive surgery of the midface^{9,32}. With 3D stereophotogrammetry, the soft-tissue surface is captured through (3D) photographs of the patient with the DRF in place³¹⁻³³. A large surface of the skin needs to be exposed for the photographs and methods relying on soft-tissues are susceptible to skin surface alterations. These methods may thus not be applicable in situations where soft-tissue variation is to be expected (e.g. swelling, nasal intubation)^{9,33}.

The dentition may be used as a reference in a direct or indirect way in Augmented Reality (AR)³⁴⁻³⁶. Wang et al. designed a method in which an intra-oral scan is matched to the CT scan (based on an Iterative Closest Point approach)³⁶. The visible teeth of the patient are tracked with a stereo camera. After registration of the stereo camera images with the intra-oral scan model, the physical world can

be augmented with the virtual planning. Exposure of the dentition, within the field-of-view, is a requirement for the workflow. Jiang et al. have proposed an AR workflow resembling the registration-free workflow described in this study³⁴. An intra-oral scan of the gypsum cast with the DRF in place is acquired, and the resulting model is matched to the CT scan using user-indicated landmarks on the dental cusps in the CT model and intra-oral scan. In the workflow described in the current study, the DRF is not positioned during the intra-oral scan, which allows an intra-oral scan of the complete dentition. Moreover, the algorithm that matches the dental model on the CT scan is not user dependent. These differences in approach may lead to an improvement in matching accuracy of the intra-oral scan³⁷, but might lack control of the splint fit on the dentition.

The registration-free navigation workflow is a method that is non-invasive and not user dependent. It is compatible with both optical and electromagnetic navigation. It could lead to a more time-efficient intra-operative procedure since intra-operative registration is obviated. This requires that the workflow is implemented in the commercialized navigation system, so that the registration matrix is determined directly rather than necessarily correcting a pre-registration as was done in this study. The workflow may be used in (partly) dentate patients whose maxillary complex is intact and continuous with the cranium. Fixation of the splint without affecting the non-invasive character of the method should be improved. Ideally, the splint would snap in place on the dentition. The method proved accurate if electromagnetic tracking was used. In contrast, a large error was found if optical tracking was used. No clear explanation for the difference between optical and electromagnetic navigation was found, although the accuracy in the optical navigation setting might improve to some extent if material stiffness and splint design are optimized. Thus, the biggest challenge toward clinical implementation of the workflow lies in reducing the error in optical navigation.

CONCLUSION

A registration-free workflow for optical and electromagnetic craniofacial intra-operative navigation was presented in this study. This method offers a non-invasive, user-independent alternative to existing registration procedures and may thus lead to increased time efficiency intra-operatively. The accuracy of the method was evaluated on five human cadaver heads; the results were compared to the accuracy measurements of maxillary bone-anchored fiducials (optical and electromagnetic) and surface-based registration (electromagnetic). The accuracy for optical and electromagnetic tracking differs greatly: registration-free navigation in electromagnetic tracking showed very promising results, while registration-free optical navigation was the least accurate of all methods. Although the workflow itself is promising, this difference in results, without a valid explanation, hampers direct clinical implementation.

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TABLES

TABLE 1. Overview of the status of the maxillary dentition of the cadavers. The DMFT score was provided, as well as the filling material and the most distal element present on either side.

Cadaver	Decayed	Missing	Span	Filled	Metal filling	Composite filling
1	-	-	17-27	12	4	8
2	8	5	17-23	-	-	-
3	-	9	14-23	1	1	-
4	-	-	17-27	1	-	1
5	2	4	17-27	2	2	-

TABLE 2. Fixed effect estimates. Bone-anchored registration with optical tracking was the model's reference category. The bold font are the registration-free parameters.

Fixed effect	Estimate	Standard dev	t value
(Intercept)	0.970	0.0348	27.86
Distance	+0.005	0.0002	23.07
EM technique	-0.064	0.0202	-3.19
Registration-free	+0.188	0.0202	9.31
Surface-based registration	+0.197	0.0202	9.78
Distance:EM technique	-0.001	0.0003	-2.35
Distance:Registration-free	-0.001	0.0003	-3.13
Distance:Surface-based registration	-0.003	0.0003	-9.73
EM technique:Registration-free	-0.253	0.0286	-8.87
Distance:EM technique:Registration-free	+0.000	0.0004	0.86

TABLE 3. Intercept and slope values from linear mixed model parameters.

Tracking technique	Registration method	Intercept	Slope
Optical	Bone-anchored fiducials	0.97	0.0049
Optical	Registration-free	1.16	0.0039

Electromagnetic	Bone anchored fiducials	0.91	0.0042
Electromagnetic	Surface-based	1.10	0.0013
Electromagnetic	Registration-free	0.84	0.0036

CAPTIONS TO ILLUSTRATIONS

Figure 1. Schematic overview of the experimental set-up. The set-up on the left is the electromagnetic tracking set-up, with the field generator positioned lateral to the cadaver head. The reference array is positioned in the holder on the splint (detailed design in *Figure 2f*). The set-up visualized on the right is the optical set-up, with the splint, with reference array attached, in place. The positions of the Allen target screws are indicated by the red circles.

Figure 2. Outline of the registration-free workflow. Steps a, b and d are identical to the steps in Part I: The CT scan (a) and intra-oral scan (d) are fused in IPS Case Designer (b). A splint-borne Dynamic Reference Frame is designed for optical tracking (e) and a splint-borne DRF holder is designed for EM tracking (f). After transformation, the DRF may be visualized in the Brainlab environment (c) and the position of the DRF may be used as T_{reg} .

Figure 3. Distribution of TRE (a,c) and \sqrt{TRE} (b,d) for the registration-free navigation approach. The dashed line represents a normal distribution with the mean and standard deviation of the outcome measure. From these histograms it is seen that the \sqrt{TRE} distribution has a better resemblance to the normal distribution.

Figure 4. Distribution of TRE (a,c,e) and \sqrt{TRE} (b,d,f) for bone-anchored optical, bone-anchored electromagnetic and soft-tissue registration respectively. Similar to *Figure 3*, the dashed line represents a normal distribution. The \sqrt{TRE} distribution also has a better resemblance to the normal distribution for these registration approaches.

Figure 5. Visualization of the regression lines for each registration method and tracking technique. The brown lines show the registration-free technique

Figure 6. Scatter plots, with kernel density estimate levels for the registration-free workflow in electromagnetic (a) and optical (b) tracking. The regression lines from *Figure 3* are superimposed. The EM measurements are less scattered than the optical measurements.

AUTHOR CONTRIBUTION STATEMENT

RS: original idea, study design, data collection, statistical analysis, lead author of manuscript

FB: original idea, study design, data collection, second author of manuscript

CK: study design, data collection, illustrations, critical review and writing of manuscript

LD: study design, critical review and writing of manuscript

LB: data collection, critical review and writing of manuscript

PH: data collection, critical review and writing of manuscript

AB: study design, critical review and writing of manuscript, supervision

TM: study design, critical review and writing of manuscript, supervision

COMPETING INTEREST STATEMENT

Brainlab AG provided the Kick navigation hardware and navigation instruments in kind for the duration of the study. KLS Martin provided the titanium screws in kind. None of the authors have competing interests to declare.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Figures

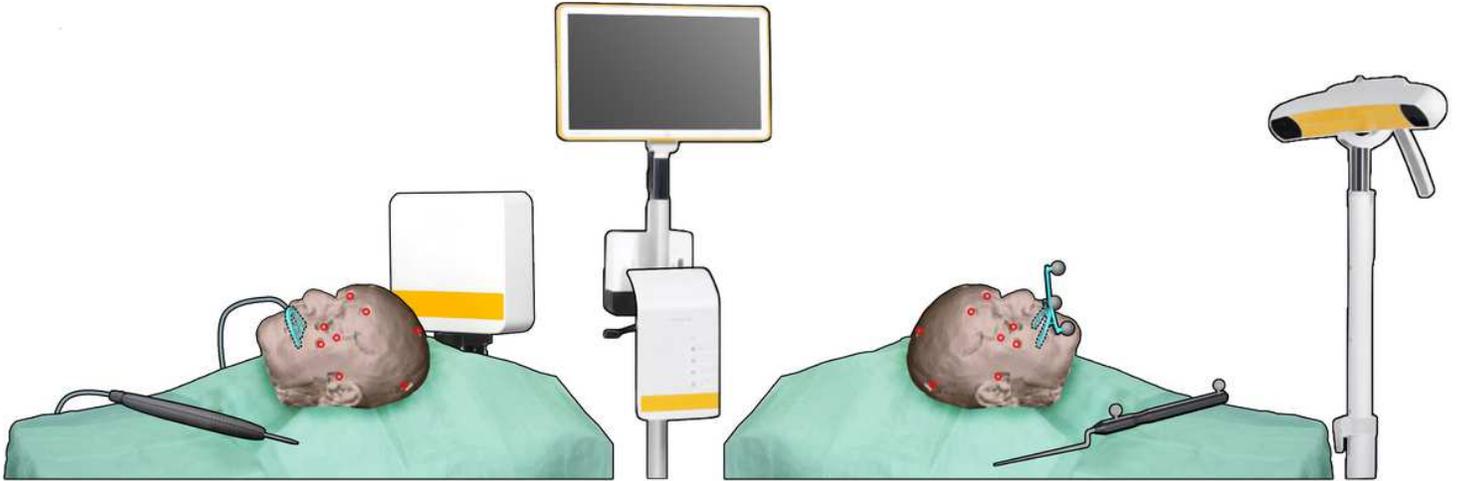


Figure 1

Schematic overview of the experimental set-up. The set-up on the left is the electromagnetic tracking set-up, with the field generator positioned lateral to the cadaver head. The reference array is positioned in the holder on the splint (detailed design in Figure 2f). The set-up visualized on the right is the optical set-up, with the splint, with reference array attached, in place. The positions of the Allen target screws are indicated by the red circles.

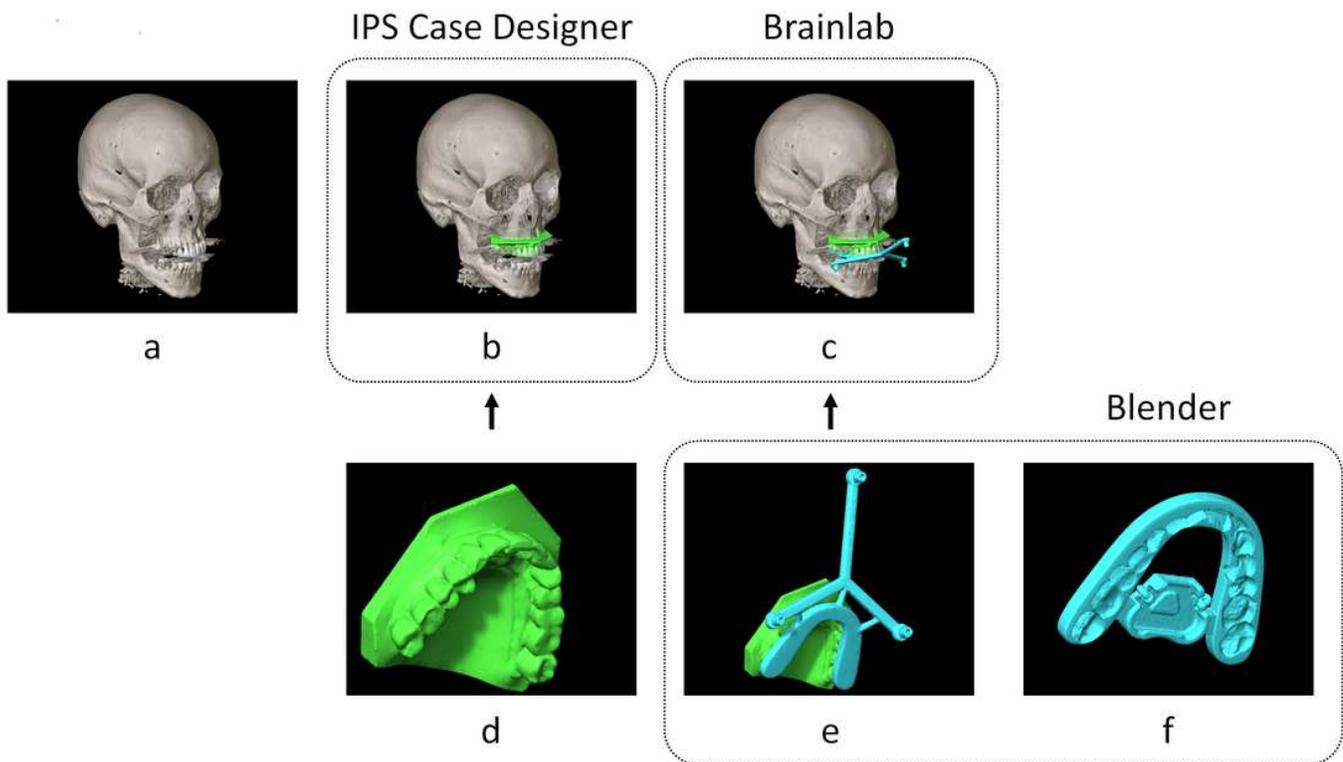


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Outline of the registration-free workflow. Steps a, b and d are identical to the steps in Part I: The CT scan (a) and intra-oral scan (d) are fused in IPS Case Designer (b). A splint-borne Dynamic Reference Frame is designed for optical tracking (e) and a splint-borne DRF holder is designed for EM tracking (f). After transformation, the DRF may be visualized in the Brainlab environment (c) and the position of the DRF may be used as T_{reg} .

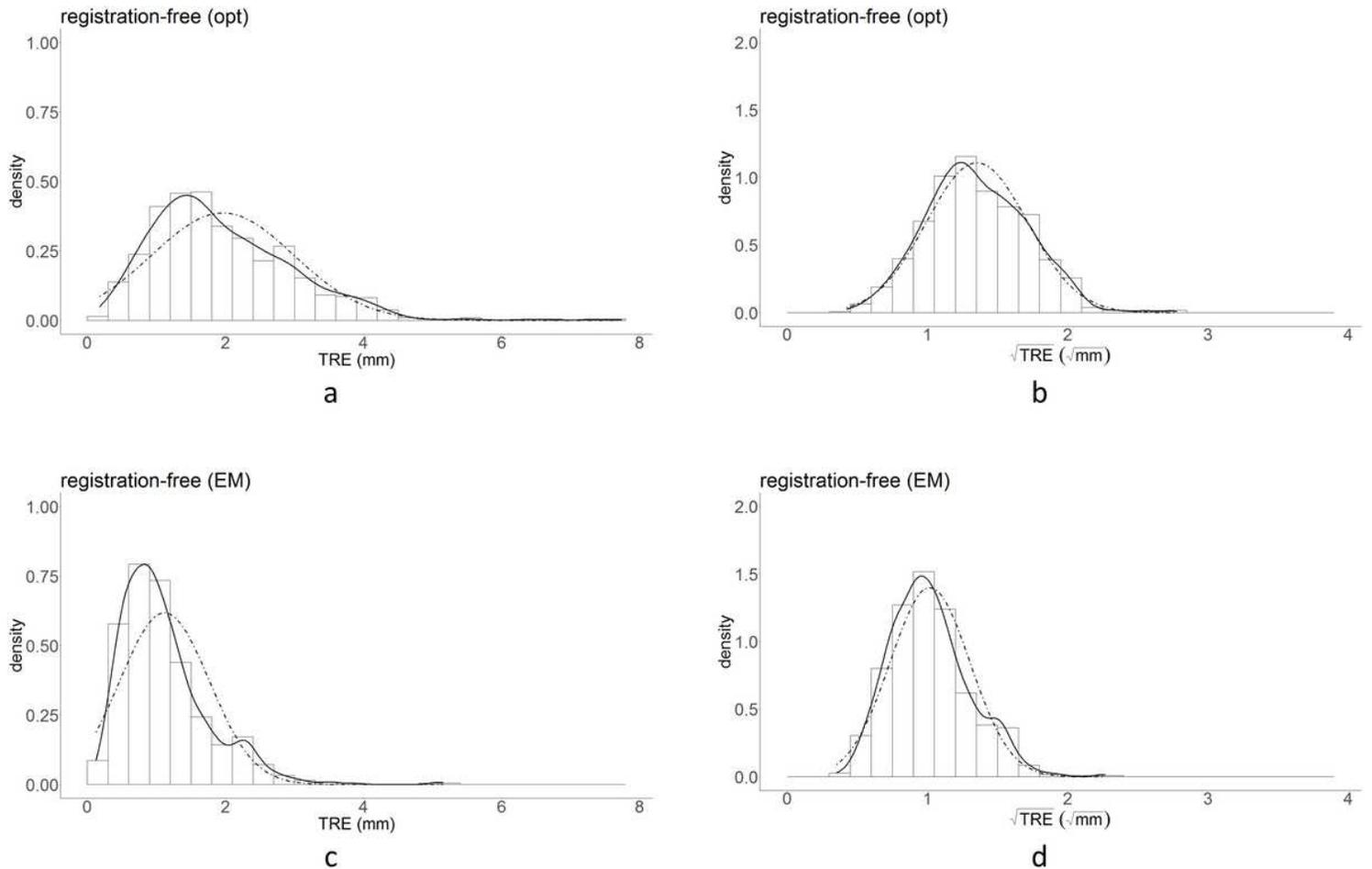


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Distribution of TRE (a,c) and \sqrt{TRE} (b,d) for the registration-free navigation approach. The dashed line represents a normal distribution with the mean and standard deviation of the outcome measure. From these histograms it is seen that the \sqrt{TRE} distribution has a better resemblance to the normal distribution.

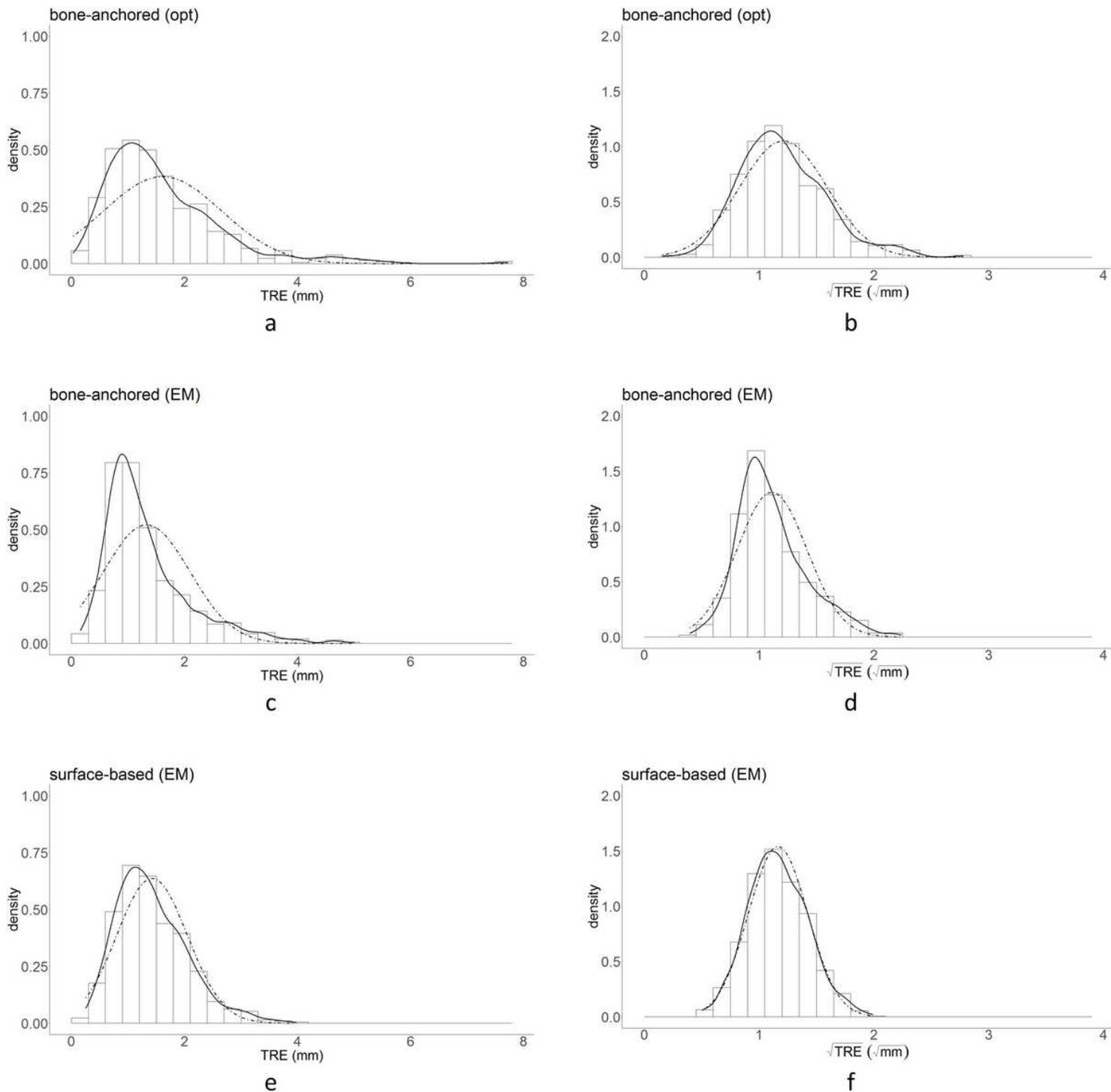


Figure 4

Distribution of TRE (a,c,e) and $\sqrt{\text{TRE}}$ (b,d,f) for bone-anchored optical, bone-anchored electromagnetic and soft-tissue registration respectively. Similar to Figure 3, the dashed line represents a normal distribution. The $\sqrt{\text{TRE}}$ distribution also has a better resemblance to the normal distribution for these registration approaches.

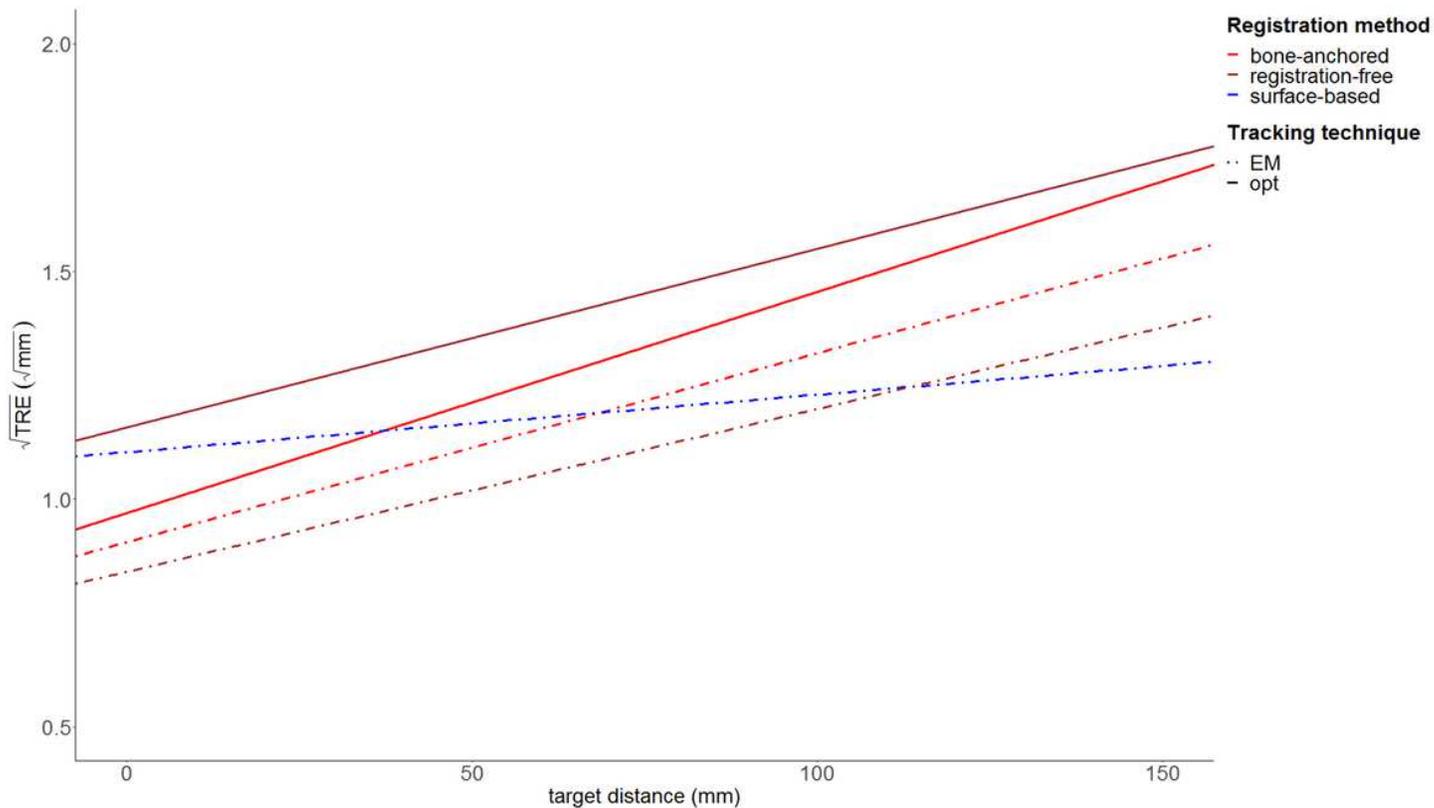


Figure 5

Visualization of the regression lines for each registration method and tracking technique. The brown lines show the registration-free technique

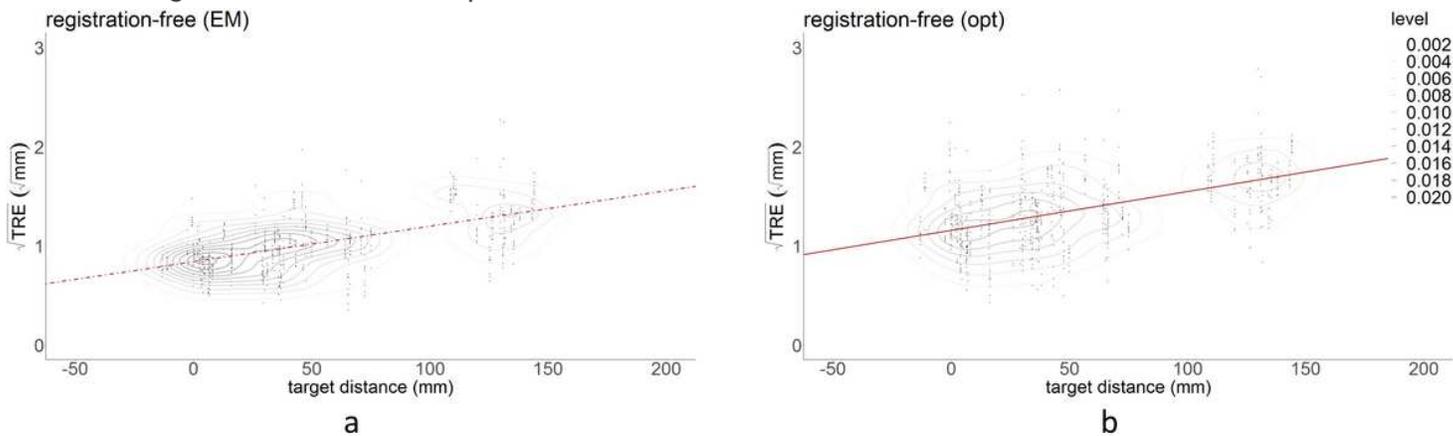


Figure 6

Scatter plots, with kernel density estimate levels for the registration-free workflow in electromagnetic (a) and optical (b) tracking. The regression lines from Figure 3 are superimposed. The EM measurements are less scattered than the optical measurements.