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ORIGINAL ARTICLE CRANIOFACIAL/MAXILLOFACIAL

Accuracy of Computational Soft Tissue Predictions in Orthognathic Surgery From Three-Dimensional Photographs 6 Months After Completion of Surgery: A Preliminary Study of 13 Patients

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Abstract
Background This study aimed at a preliminary evaluation of the accuracy of computed three-dimensional (3D) predictions in orthognathic surgery by comparing predicted and real postoperative results.
Methods Pre- and postoperative 3D photographs and time-matching computed tomography (CT) and cone-beam CT scans of the face of 13 patients with dentofacial deformities were analyzed. Three-dimensional photographs were fused with preoperative CT data using dedicated software (3dMDvultus, version 2.2.0.8). Postoperative CT data were superposed on the preoperative skull. With an activated rendering function, the osteotomies were simulated in the preoperative CT data and the bony segments moved to their real postoperative position, resulting in a textured soft tissue prediction. This computed skin surface was compared with the real postoperative result by dividing the face into a surgically treated lower half and an untreated upper half. A statistical quantitative analysis of the surfaces was performed.
Results The mean differences between surfaces were +0.27 mm for the untreated upper half and –0.64 mm for the surgically treated lower half ($p < 0.001$). Averaged distributions of absolute errors showed more discrepancies between predicted and real postoperative results in the lower half of the face. Errors exceeding 3 mm were encountered in 4 % of the upper halves versus 29.8 % of the lower halves ($p < 0.001$).
Conclusions The accuracy of a specific software platform for predicting 3D soft tissue changes after surgery was insufficient.
Level of Evidence IV This journal requires that authors assign a level of evidence to each article. For a full description of these Evidence-Based Medicine ratings, please refer to the Table of Contents or the online Instructions to Authors www.springer.com/00266.

Keywords 3D photograph · Orthognathic surgery · Simulation · Prediction · 3dMD

Historically, planning and evaluation of orthognathic surgical outcomes have been executed with two-dimensional (2D) radiographs and 2D photographs [4, 5, 12, 25]. Currently, efforts are directed toward developing realistic three-dimensional (3D) craniofacial models for planning, simulating, and documenting orthognathic surgery and for predicting its outcome, mirroring the exact postoperative result [8, 18]. One of the main advantages is that surgeons can operate on a patient virtually until an aesthetically satisfactory result is obtained without creating further costs or risks [8]. Ideally, this result should be precisely reproducible in operating theaters. Although very precise osteotomies in all sorts of shapes can be performed, inability to predict changes in facial soft tissue accurately, the main important point for the patient, limits the use of 3D virtual orthognathic surgery [18, 24, 25].

The accuracy of prediction software has been studied in a limited number of patients without a textured surface [1]

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because results are complex and difficult to evaluate. The approach used by Cevidanes et al. [7] to investigate bony morphometric changes 1 year after surgery illustrates well the complexity of the work. In their study, they used an initial software to convert radiologic data, a second software to segment bone, a third software to register and superimpose structures, and finally, a fourth software to assess differences between two structures in a color-coded image.

Currently, several integrated simulation and prediction software packages are commercially available. Reportedly, the 3dMDvultus software platform (3dMD, Altanta, GA, USA) can serve as a guideline for surgery because the soft tissue changes are automatically reconstructed and allow an evaluation of the aesthetic results so that the best treatment plan can be chosen [23]. The Internet Web site of the software states more cautiously that the software "animates the possible dynamics of soft tissue deformation" (www.3dmd.com).

Thus, the current study aimed to evaluate the prediction accuracy of soft tissue changes of a specific software "out of the box" without using further software tools or any sort of optimization. Predicted images were statistically compared with real postoperative results 6 months after surgery.

Materials and Methods

Patients

A retrospective search of clinical notes for patients treated at the Geneva University Hospitals, Geneva, Switzerland, between 2010 and 2012, with available pre- and postoperative head computed tomography (CT) or cone-beam CT (CBCT) scans and time-matching 3D facial stereo photogrammetric scans (within 24 h) was conducted. The following additional inclusion criteria were met by 13 patients (8 females and 5 males; mean age 25.2 years):

(1) The patient underwent orthognathic surgery without bone grafting (see Table 1 for details)
(2) The postoperative 3D photogrammetric scans and CT/CBCT were taken at least 6 months postoperatively
(3) The patient had no previous history of facial surgery or trauma
(4) The patient had no congenital craniofacial deformity.

The study followed procedures in accordance with the 1975 Declaration of Helsinki, as revised in 2000, and was approved by our local ethics board.

CT and CBCT Scan Acquisition

Imaging was performed with a 64-slice CT scanner (Siemens Sensation 64; Germany: 120 kV; 240 mAS; 2 × 32 detectors; increment, 0.7 mm; collimation, 64 × 0.6; slice thickness, 1 mm; matrix, 512 × 512 pixels; gantry tilt, 0°) or with a CBCT scanner (NewTom VGi, QR srl, Verona, Italy; image detector: amorphous silicon flat panel, 20 × 25 cm; image acquisition, 360/480 images; 360° rotation). As soon as the equipment was purchased, CBCT was performed to reduce the patient irradiation dose. Preoperatively, six patients had conventional CT, and seven had CBCT. All the patients underwent CBCT postoperatively. All CBCTs were performed by instructed personnel or in the presence of one of the authors, with the head in natural position, lips at rest, neutral facial expression, open eyes, and intercuspidation without visible activation of the muscles of mastication.

Table 1 Sex and age of patients, type of osteotomies, and bone movements performed

Patient	Sex/age	Le Fort 1, movement of the maxilla (mm)	BSSO, movement of the mandible (mm)	Genioplasty, movement of the chin (mm)
1	F/19	2	5	–
2	M/40	8	8	–
3	F/61	9	9	8
4	M/20	–	5	–
5	F/15	5	1	–
6	M/38	10	10	–
7	F/20	5	1	–
8	M/20	3	–3	7
9	M/20	3	4	11
10	F/17	6	12	–
11	F/17	6	2	–
12	F/16	–	4	–
13	F/23	–	4	10

BSSO bilateral mandibular sagittal split osteotomy of the mandible

A positive value is an advancement of the bone, a negative value represents a setback movement. The movement of the maxilla is measured at orthognathic point A (the most posterior point of the maxilla's anterior surface in a midsagittal plane). The movement of the mandible is measured at orthognathic point B (the most posterior point of the mandible's anterior surface in a midsagittal plane). The chin movement is measured at orthognathic point P (the most anterior point of the chin in a midsagittal plane)

3D Facial Surface Image Acquisition

Three-dimensional facial stereo photogrammetric scans were taken with a 3dMDTrio System multicamera (3dMD, Atlanta, Georgia, USA) with a capture speed of 1.5 ms and a 200° full face capture. The system was equipped with three modular units, each consisting of two machine vision stereo cameras for geometry, one machine vision color camera for texture, and one speckle projector.

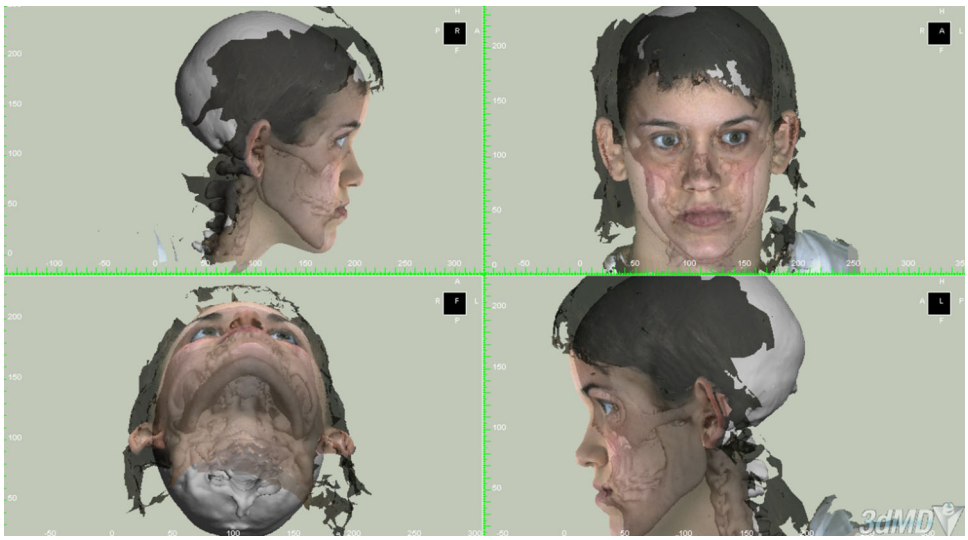

Fig. 1 Three-dimensional (3D) soft tissue photograph of a patient with fused underlying hard tissue

All 3D photographs were taken with the head in natural position, lips at rest, neutral facial expression, open eyes, and intercuspidation without visible activation of the muscles of mastication. All the patients were guided and observed by one of the investigators (A.T.), who took all the photographs.

Virtual Surgery and Computer Image Analysis

Fusion of Preoperative 3D Photograph and Preoperative CT/CBCT

The CT and/or CBCT scan images in DICOM (Digital Imaging and Communications in Medicine) format and the textured photogrammetric scan images in.tbs format were imported to the 3dMDvultus software platform (3dMDvultus® software, version 2.2.0.8; 3dMD). The untextured CT/CBCT skin surface was extracted by adjusting the appropriate Hounsfield values. The preoperative 3D photograph then was uploaded and fused with the untextured CT/CBCT skin surface via a semiautomated built-in fusion tool. Once the fused position was achieved, the bony skull was extracted, again by manipulating the Hounsfield values. This resulted in a 3D photograph with underlying hard tissue (Fig. 1).

Fusion of Pre- and Postoperative CT/CBCT Data

Using the aforementioned procedures, the postoperative bony skull was extracted and fused with the preoperative skull (Fig. 2) by matching bone areas untouched by surgery (nasal bone, skull base, clivus, and the malar prominence of the zygomatic bone).

Virtual Osteotomies and Soft Tissue Prediction

Subsequently, the 3D bone segments were reproduced in the preoperative skull (Fig. 3) according to the real postoperative CT. The software rendering function (mass spring model) was activated. After the soft tissue had been faded out, the osteotomy segments were moved onto the real postoperative position. Once they were correctly placed, the soft tissue rendering was reactivated, resulting in the computer-generated textured facial soft tissue prediction.

Fusion of Predicted Soft Tissue Changes With Real Postoperative Results and Preparation for Statistical Analysis

The 3D photographs of predicted and real postoperative soft tissue were fused as described earlier using only areas untouched by surgery (forehead, bridge of nose, temple) (Fig. 4). Next, hair and neck were completely zoomed out. We arbitrarily chose to place a horizontal plane at the inferior border of the right pupil to divide the superimposed photographs into two halves. This produced a fused upper, non–surgically treated part of the face and a lower part comprising the overlay of the predicted and real postoperative results. The software also was able to display a color-coded surface (otherwise not used in our article) for simpler assessment of individual sites (Fig. 5).

The software provided the following additional numeric results for the upper and lower parts: the number of mass spring model points used for the comparison, the mean difference in millimeters between these points, the standard deviation of the distribution of the differences, and a graph

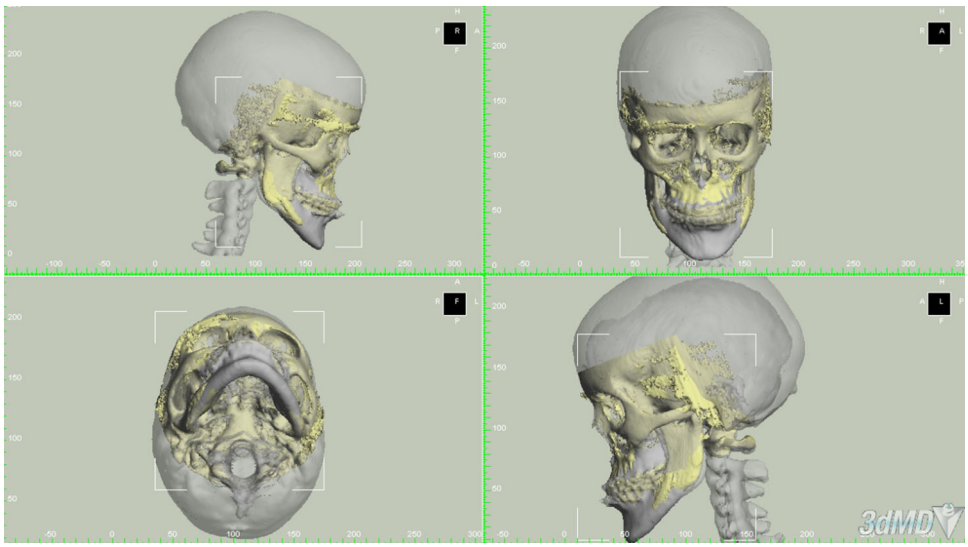

Fig. 2 Fusion of the pre- and postoperative three-dimensional (3D) computed tomography (CT) scan reconstructions. The preoperative scan is *gray*, and the postoperative scan is *yellow*. The latter is smaller in size because it is a cone-beam (CB) CT (CBCT) reconstruction. The picture does not allow an assessment of the bone position and serves only to explain the method

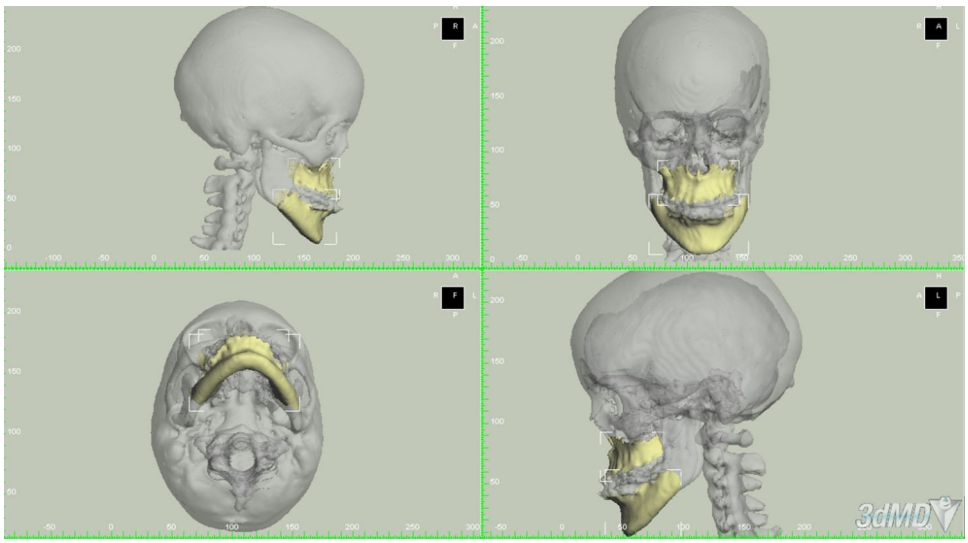

Fig. 3 Preoperative three-dimensional (3D) computed tomography (CT) scan reconstruction in *gray*. The intraoperatively performed osteotomies for the maxilla and the mandible are simulated in *yellow*. These are the segments that are moved to obtain the soft tissue prediction

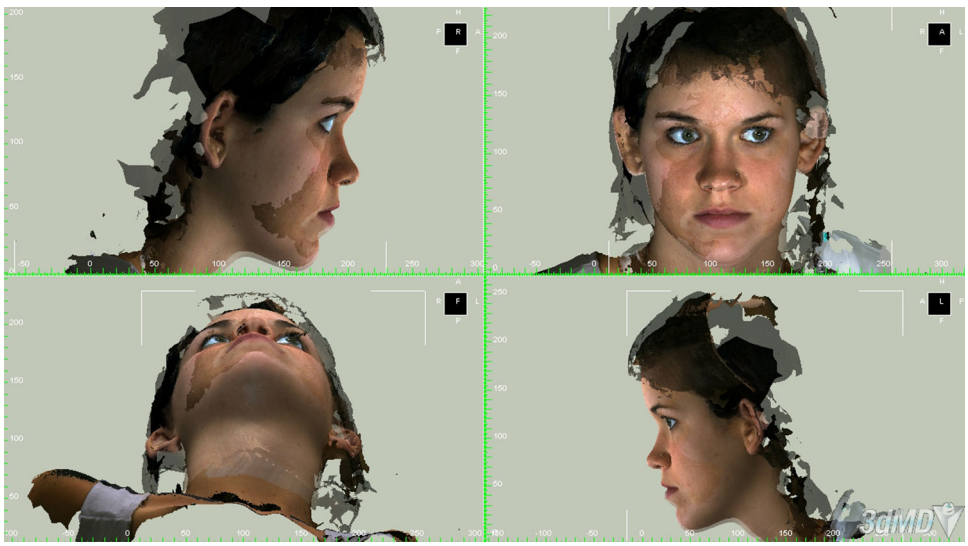

Fig. 4 Fusion of the real postoperative three-dimensional (3D) photograph and the computer-generated soft tissue prediction. The overlay of soft tissue in this example is best seen in profile pictures of the chin and lower lip. The fusion does not allow an assessment of the soft tissue and serves only to explain the method

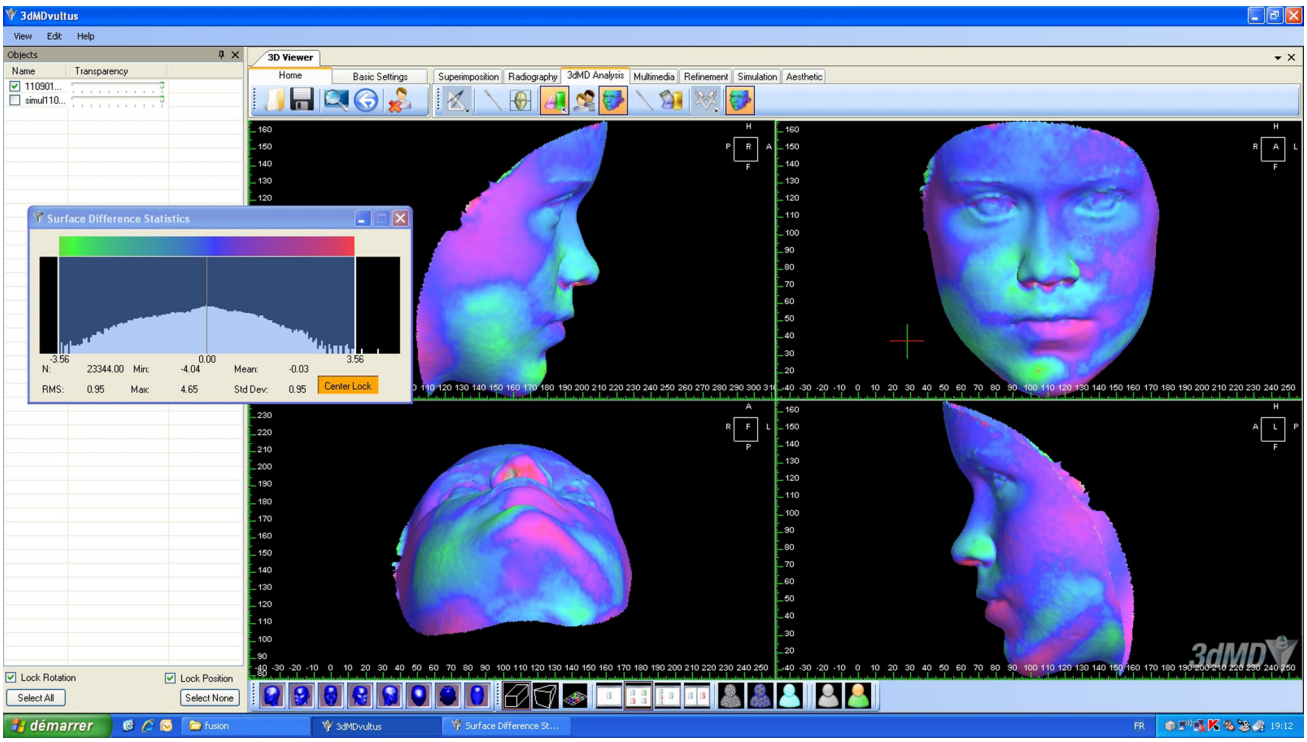

Fig. 5 For better visual assessment of specific sites, the software also can display a color-coded surface (otherwise not used in the article)

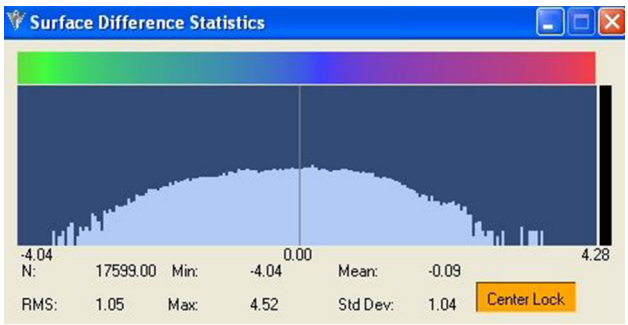

Fig. 6 Distribution of the differences shown by the software. The values correspond to the values for the *lower* part of patient no. 7, our patient example. As a general rule, it represents a nonparametric distribution of the differences. In this example, the distribution coincidentally approximates a normal distribution

showing the distribution of these differences (Fig. 6). The differences between the predicted and the real postoperative photographs were interpreted as an error. The data were obtained for the upper and lower parts of each patient's face. Because no surgery was performed on the upper part, the fusion differences in the upper part gave information on the reproducibility and reliability of the software. The differences between the two surfaces in the lower part represented the precision of the prediction made by the software, including the aforementioned precision of the method.

Statistical Analysis

Initially, all the mass spring model points were extracted from the distribution image (Fig. 6) as follows. After the images had been digitized with the R package (ReadImage), the distribution curves were selected by a single operator (C.C.), and coordinates were derived using the digitize package [20]. This extraction allowed a reconstitution of all single mass spring model values to be available on one photograph.

We then compared the soft tissue between the lower and upper parts of the face. The reported mean error for each patient was averaged using metaanalysis methods for aggregated data such as the mean errors reported. The principle was to average the reported means using the standard errors as weights.

A model with random effects was used to account for heterogeneity across patients [9]. This heterogeneity was described by the I^2 statistic, which ranges from 0 to 100 % [14]. The analysis was conducted with the upper and lower parts of the face. To compare the errors between the parts, a metaanalysis of difference of means with random effects was performed [10].

A z-test examined the hypothesis that the averaged difference of errors between upper and lower facial parts equals 0 mm [10]. Accounting for misleadingly balanced negative and positive errors, we also assessed the averaged

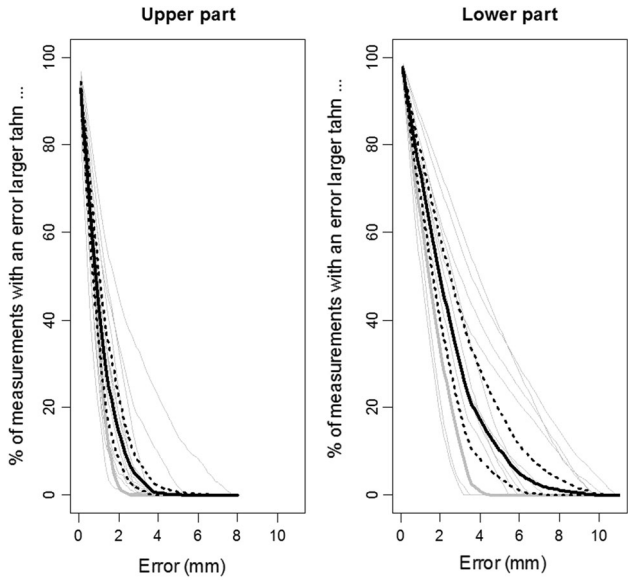

Fig. 7 Reverse cumulative distributions of the errors of all the mass spring points in the *upper* and *lower* parts. The individual curves of all 13 patients are shown in *gray*, and the average of all the patients is in *black*. The *dashed black lines* are the 95 % confidence bands

distribution of the absolute errors as follows: (1) for a given level of absolute error (e.g., 1 mm), we extracted the proportion of mass spring points above this level from the distribution images (Fig. 6); (2) We repeated the analysis for the various possible levels of error [22]. We also compared the averaged proportions in both parts of the face for errors of 1, 2, and 3 mm, applying a bivariate approach for metaanalysis with random effect [15]

In addition, the results were graphically represented by a curve, the reverse cumulative distribution (Fig. 7) [21].

Results

Mass Spring Point Analysis

Depending on how much skin was visible, the number of points analyzed by the software ranged from 4,888 to 20,298 in the upper part of the face and from 15,378 to 27,667 in the lower part. The distributions were more scattered in the lower part of the face than in the upper part. The data for all the patients are summarized in Table 2.

Surface Analysis

The surface difference analysis of all points showed an averaged mean error of +0.27 mm (95 % confidence interval [CI] 0.15–0.40) for the upper part of the face and –0.64 mm (95 % CI –0.99 to –0.31) for the lower part. The resulting difference was +0.92 mm (95 % CI 0.61–1.23), which was statistically significant ($p < 0.001$).

The I^2 statistic was 99.91 % for the upper part of the face and 99.96 % for the lower part, indicating significant heterogeneity for both parts. The surfaces of the upper and lower face showed important differences. A small error

Table 2 Results for the distribution of error (cf. Fig. 7) as provided by the software, detailed per patient

Patient	Upper half			Lower half		
	n[a]	Mean[b] ± SD	Min/max	n[a]	Mean[b] ± SD	Min/max
1	6,582	0.14 ± 1.32	–5.17/4.18	16,407	–3.35 ± 2.87	–10.94/4.63
2	20,298	0.32 ± 0.9	–4.45/3.58	21,737	0.28 ± 1.66	–3.87/10.11
3	4,888	0.80 ± 1.87	–8.80/7.75	16,438	–0.38 ± 3.73	–10.34/11.93
4	12,418	0.52 ± 0.52	–2.94/3.28	21,029	0.02 ± 1.05	–10.83/9.52
5	10,130	0.18 ± 0.80	–3.95/3.45	16,717	–0.36 ± 0.83	–3.32/2.50
6	11,659	0.67 ± 1.08	–5.98/6.68	27,667	0.22 ± 2.39	–5.55/10.66
7	6,320	0.15 ± 0.54	–3.79/4.65	17,599	–0.09 ± 1.04	–4.04/4.52
8	6,069	0.19 ± 0.97	–3.24/4.23	15,378	–1.96 ± 2.78	–9.80/6.65
9	13,821	0.03 ± 0.51	–2.49/3.74	20,728	–0.93 ± 1.76	–6.39/4.46
10	7,524	0.43 ± 0.82	–3.09/4.05	20,087	–0.84 ± 2.08	–5.99/5.30
11	5,876	0.14 ± 0.55	–7.45/7.51	19,288	–0.55 ± 1.62	–7.14/4.66
12	6,433	–0.04 ± 0.51	–3.85/3.55	15,834	0.09 ± 1.55	–3.40/6.55
13	9,547	0.01 ± 0.31	–6.86/3.84	17,903	–0.56 ± 1.97	–9.78/4.70

SD standard deviation, *Min* largest negative value measured, *Max* largest positive value measured

[a] n is the number of mass spring points analyzed. It varies according to the amount of visible skin. For instance, in the upper half, patient 2 is a completely bald man, and patient 3 is a teenager with a modern haircut covering parts of his forehead. In the lower half, the number of points is more consistent (15,378–21,737 points)

[b] The mean is the mean difference between the two fused surfaces

Table 3 Percentages of mass spring points with an error lower than ±1 mm and those exceeding ±1, ±2, and ±3 mm

	Upper part % (95 % CI)	Lower part % (95 % CI)	*p* value
<±1 mm	57.4 (49.1–65.6)	26.9 (21.9–32.4)	<0.001
>±1 mm	42.6 (34.4–50.9)	73.1 (67.6–78.1)	<0.001
>±2 mm	14.3 (7.9–22.2)	49.5 (40.2–58.8)	<0.001
>±3 mm	4.0 (1.5–7.8)	29.8 (19.0–41.8)	<0.001

CI confidence interval

(<1 mm) was present in more than half of the surface points in the upper part of the face, but in only one fourth in the lower part (Table 3). Moreover, important errors (>3 mm) were found more frequently in the lower part of the face (29.8 %) than in the upper part (4.0 %). The averaged proportions of surface points with an absolute error greater than 1, 2, or 3 mm are detailed in Table 3. The errors were significantly larger in the lower part of the face ($p < 0.001$).

The individual patient results are further shown in Fig. 7. The interpretation of the curves is equal to that for the survival curves, showing the percentage of error in millimeters. For instance, averaged errors of 4 mm or more were found to be approximately 0 % in the upper part of the face, whereas they accounted for about 20 % of the errors in the lower part.

Discussion

The current study showed a statistically significant lack of accuracy in 3D prediction, and it was concluded that the predictions were not reliable. Previous research on the reproducibility, repeatability, and reliability of different investigators of 3D soft tissue landmarks has already defined the level of accuracy required for 3D applications [11, 19]. If repeatedly measured mean differences of the distances between two identical landmark points are less than 0.5 mm, it is considered highly accurate and reproducible. A mean difference of 0.5–1.0 mm accounts for a less accurate but clinically irrelevant divergence, whereas a difference exceeding 1 mm is clinically relevant.

We can extrapolate these definitions of accuracy when comparing the two photographs we investigated in our study. Thus, a divergence of less than 1 mm between prediction and reality is clinically irrelevant, whereas everything greater is relevant. It is worth mentioning that most published research worked with 3D spatial resolutions of about 0.5 mm and that the overall variance measurements of our specific imaging system are estimated to be only 1.5 % [3, 6, 7].

The results showed that the mean error of registration and fusion for the non–surgically treated upper half of the face was very low. However, when the predicted lower half of the face was examined, relevant discrepancies were observed (Table 1). Applying the aforementioned levels of accuracy resulted in unsatisfactory overall results. However, no comparison with other published data was possible given the absence of similar studies. One analogous approach for investigating (untextured) 3D predictions in a group of heterogeneous osteotomies has been published recently, but it used landmarks and not the entire surface of the face [1]. To our knowledge, no other study has investigated the precision of textured 3D predictions for the entire face.

Studies concerning computer-assisted surgery or computer-assisted design and manufacturing in the maxillofacial field usually are based on radiologic data. These are obtained by either conventional CT or CBCT, the latter being available in most hospitals only recently. As findings have shown, the quality of CBCT volumes equals that of conventional CTs in the maxillofacial sphere while the patient is subjected to a lower radiation dose [2, 13, 17]. Additionally, a comparison of conventional CT and CBCT 3D reconstructions showed surface correspondences higher than 0.5 mm for the entire surface [16]. Because one radiologic golden rule is that patients should be irradiated as little as possible, recent studies have modified their protocols during the acquisition of data to include CBCT volumes and have examined mixed radiologic data originating from both CT and CBCT [1, 26]. This study was no exception.

Software packages offering simulation and soft tissue predictions in orthognathic surgery have been commercially available for 5–10 years. Simulation is highly interesting because it allows the surgeon to try different surgical options before performing them in the theaters and permits better preoperative planning.

Numerous articles describe the new 3D techniques enthusiastically, and it is unanimously agreed that their application will change orthognathic surgery [19, 23–25]. But no published reports have evaluated the predictions for several reasons: (1) it is difficult to obtain CT or CBCT data of patients before and after surgery, and patient groups are inevitably small [1]; (2) The predictions are very time consuming and currently impede routine clinical applications [8, 24]. Even in experienced hands, software manipulation can easily take 3–4 h for just one patient; (3) It seems that the soft tissue prediction results are not reliable and cannot be shown to patients.

Critical evaluation of 3D predictions involves multiple difficulties, and considerable uncertainty currently exists regarding how to obtain and analyze 3D data [6]. Head posture influences the soft tissue in an unknown manner.

Extractions from DICOM data, the semi-automated fusion of CT/CBCT data, and 3D photographs remain examiner dependent and are not necessarily reproducible as long as they are not completely automated [7]. Consequently, if errors in prediction are found, it is not very clear whether they are caused by software handling or by the prediction model itself.

Our study also experienced these problems. Nevertheless, our method eliminated one major source of error. By fusing pre- and postoperative CT scans and moving the bone segments into their real postoperative position, we purged discrepancies between planned and actually obtained postoperative bone positions. Therefore discrepancies between planning and performing surgery were eliminated.

In conclusion, this preliminary study demonstrated that the accuracy of a specific software platform for predicting 3D soft tissue changes in orthognathic surgery as a daily routine is insufficient. Without a doubt, the result should be interpreted with caution given the limited number of patients in the study. In no case does it allow definitive conclusions to be drawn, which can be provided only at the end of an actual ongoing prospective study in our department.

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