Reproducibility of landmark identification on different CT images of the head in three-dimensional cephalometry

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REPRODUCIBILITY OF LANDMARK IDENTIFICATION ON DIFFERENT CT IMAGES OF THE HEAD IN THREE-DIMENSIONAL CEPHALOMETRY

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ABSTRACT

Cephalometry is the scientific measurement of the head and is a widely used technique in orthodontics and craniofacial surgery. In a previous study, a new method for three-dimensional computed tomography (3D CT) cephalometry was investigated, in which landmarks are semi-automatically calculated from a 3D triangulated surface model of the skull. It was shown that high intra- and interobserver reproducibility can be achieved when several analyses are performed on the same 3D model. However, when the head is oriented in a different way during CT scanning, a different triangulated surface will be obtained. Therefore, the reproducibility of landmark identification on different CT images of the patient's head was studied. Pre- and postoperative images were used to construct two triangulated models of the skull, a registration procedure was carried out to orient them in the same way and 15 landmarks, situated on the non-operated part of the skull, were calculated. The effect of the altered orientation during scanning was investigated by calculating the distances between the pre- and postoperative landmarks. The mean distance over 12 patients and 15 landmarks varies between 0.60 and 0.67 mm, depending on the number of smoothing iterations applied on the surfaces. For 10 smoothing iterations, the mean distance over the patients varies between 0.20 and 1.33 mm (mean = 0.60 mm) and the maximum distance over the patients varies between 0.33 and 3.57 mm (mean = 1.33 mm). These variations should be kept in mind when comparing pre- and postoperative data of patients treated with craniofacial surgery.

1. INTRODUCTION

Cephalometry is the scientific measurement of the head through the identification of reference points or anatomical landmarks and is a widely used technique in orthodontics and craniofacial surgery. It has been shown that computed tomography data and three-

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dimensional rendered images can provide additional useful information to conventional radiographs for patient management [1,2] and allow evaluation of complex anatomies such as asymmetrical cases [3]. The anatomical landmarks are traditionally identified by manual point-picking on a 3D surface rendering of the skull and therefore, reproducibility mainly depends on the experience and judgement of the examiner. In a previous study, a new method for 3D CT cephalometry was investigated, in which the landmarks are semi-automatically calculated from a 3D triangulated surface model of the skull. The cephalometric tools were implemented using pyFormex (http://pyformex.berlios.de), which is an open-source program under development at bioMMeda that provides a wide range of operations on (triangulated) surface meshes. It was shown that high reproducibility can be achieved when several analyses are performed on the same 3D model (intraobserver standard deviation $\leq$ 0.15 mm and interobserver difference between mean values of examiners $\leq$ 0.10 mm for 8 out of 10 landmarks) [4]. However, when the head is oriented in a different way during CT scanning, a different triangulated surface will be obtained. Therefore, the reproducibility of landmark identification on different CT images of the patient's head was studied.

2. MATERIALS & METHODS

2.1 3D reconstruction

Pre- and postoperative CT images of 12 patients that underwent jaw surgery were used to construct two triangulated models of the same skull. All images had an intra-slice resolution of 0.48 mm and an inter-slice resolution of 0.60 mm. Segmentation and 3D reconstruction of the skull was done using Mimics® (Materialise NV, Leuven, Belgium), by applying the predefined threshold interval for bone (226-3071 HU) and the optimal 3D reconstruction quality parameters (contour interpolation, two iterations of Laplacian smoothing and three iterations of triangle reduction).

2.2 Landmark calculation

The surface models were imported into pyFormex and for each patient, 15 landmarks, situated on the non-operated part of the skull, were semi-automatically calculated (see Table 1). The following strategy was used and is illustrated in Figure 1:

- The examiner selects a surface region on the triangulated model of the skull (Figure 1: left and middle).
- The quality of the surface region is improved (Figure 2: right).
  - The surface region is smoothed to remove noise and obtain more continuous surface normals. To limit the volume change, a low-pass filter is used [5], which alternates between two steps of Laplacian smoothing: a shrinking step and an unshrinking step.
  - The surface region is refined to allow interpolation between the original vertices. A subdivision algorithm based on the modified butterfly scheme, which guaranties C1 continuity (i.e. continuous tangent planes) [6], is used to split every triangle into four new triangles during each of three iterations.
- Finally, depending on the geometrical shape of the region, the landmark is calculated as follows:
  - convex/concave geometry: the extreme point of the surface region;
  - saddle-shaped geometry: the extreme point of an intermediate line region,

which is represented by natural cubic splines (Figure 2: right).

Because the landmarks are calculated as extreme points, their coordinates depend on the orientation of the skull model. Therefore, the skull model is oriented with pyFormex, using a standardised reference system based on some of the landmarks.

Table 1. Landmarks used in this study.

Landmark	Abbreviation	Geometry
Basion	B	saddle-shaped
Clinoid Anterior Left	CAL	convex
Clinoid Anterior Right	CAR	convex
Clinoid Posterior Left	CPL	convex
Clinoid Posterior Right	CPR	convex
Mastoid Left	ML	convex
Mastoid Right	MR	convex
Nasion	N	saddle-shaped
Orbitale Left	OrL	saddle-shaped
Orbitale Right	OrR	saddle-shaped
Porion Left	PoL	saddle-shaped
Porion Right	PoR	saddle-shaped
Sella Superior	SS	average of other points
Zygion Lateral Left	ZLL	convex
Zygion Lateral Right	ZLR	convex

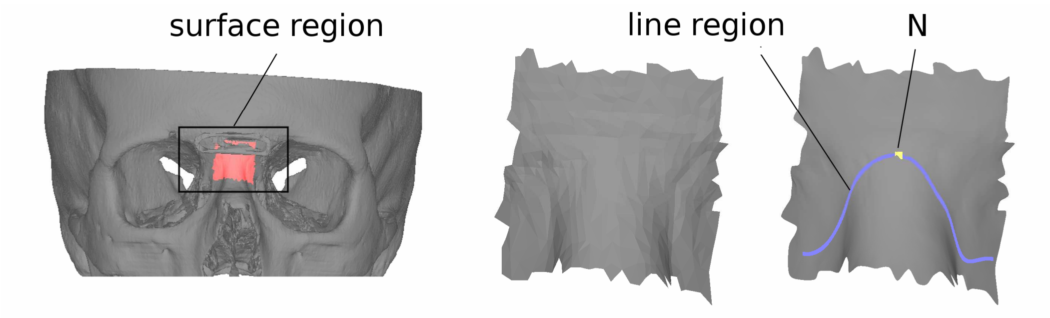

Figure 1. Landmark calculation illustrated for the point Nasion (N).

2.3 Landmark reproducibility

The variable head position during scanning causes a difference in orientation between the pre- and postoperative CT images. To compare the pre- and postoperative landmarks, however, the skull models should be oriented in the same way. Orienting both skulls using pyFormex, might result in a slightly different orientation, since the reference system itself is based on the landmarks. To solely focus on the landmark variability resulting from the difference in triangulation, the postoperative models were oriented with pyFormex and the preoperative models were transformed to the same reference system by using a registration procedure in Mimics.

First, the area change resulting from the quality improving operations (smoothing and refinement) was calculated for eight different numbers of smoothing iterations (ranging from 0 to 100). Then, the influence of smoothing on the landmark coordinates was studied. Therefore, the distance between the landmarks calculated without smoothing and the landmarks calculated with smoothing, was computed. The mean distance over the 24 skull models was calculated for each landmark and number of smoothing iterations. Finally, the effect of using different triangulated models was investigated by calculating the distance between the pre- and postoperative landmarks. Again, the mean distance for each landmark and number of smoothing iterations was computed.

3. RESULTS

The mean absolute area change is shown in Table 2 and ranges from 0.49 % (4 iterations) to 1.93 % (100 iterations). Figure 2 shows the mean distance between the coordinates calculated without and with smoothing for the 15 landmarks and a mean value for all landmarks (Mean). The values for seven numbers of smoothing iterations (n) are displayed. The overall Mean varies between 0.19 and 0.49 mm. Figure 3 shows the mean distance between the pre- and postoperative landmarks for eight numbers of smoothing iterations. The overall Mean varies between 0.67 and 0.60 mm. The smallest mean distances were obtained for 10 smoothing iterations, ranging from 0.20 (SS) to 1.33 mm (ZLR) (Mean = 0.60 mm). The maximum distance per landmark ranges from 0.33 (Ba) to 3.57 mm (ZLR) (Mean = 1.33 mm).

Table 2. Area change resulting from the quality improving operations

Number of smoothing iterations	0	4	10	20	40	60	80	100
Mean absolute area change (%)	0.84	0.49	0.72	1.04	1.44	1.67	1.82	1.93

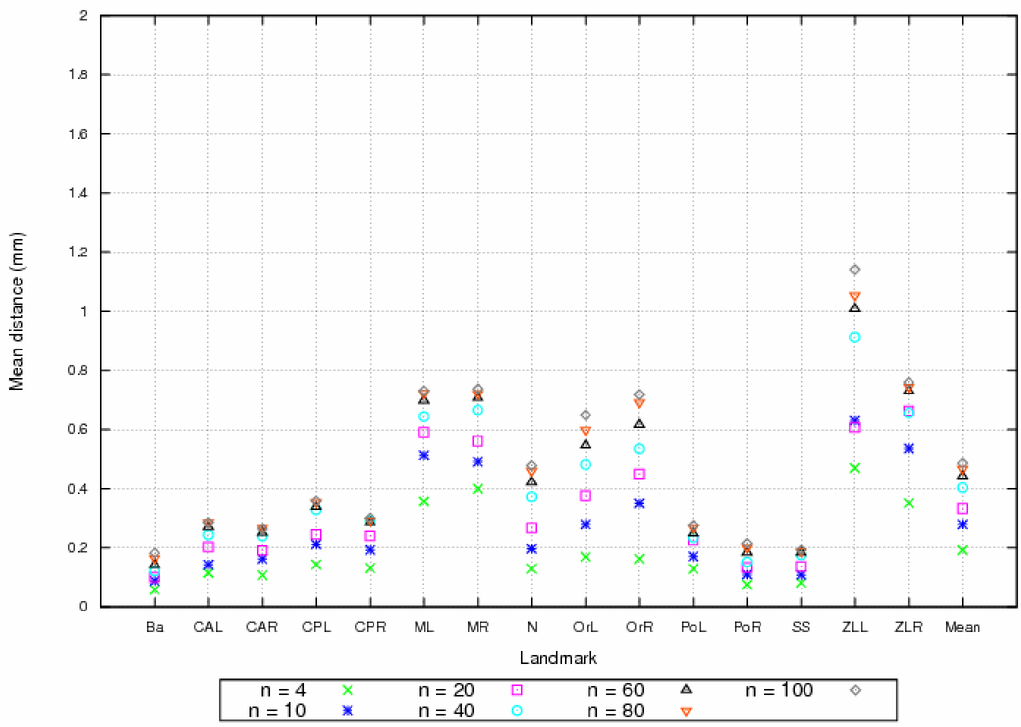

Figure 2. Mean distance between the landmarks calculated without and with smoothing (n=number of smoothing iterations).

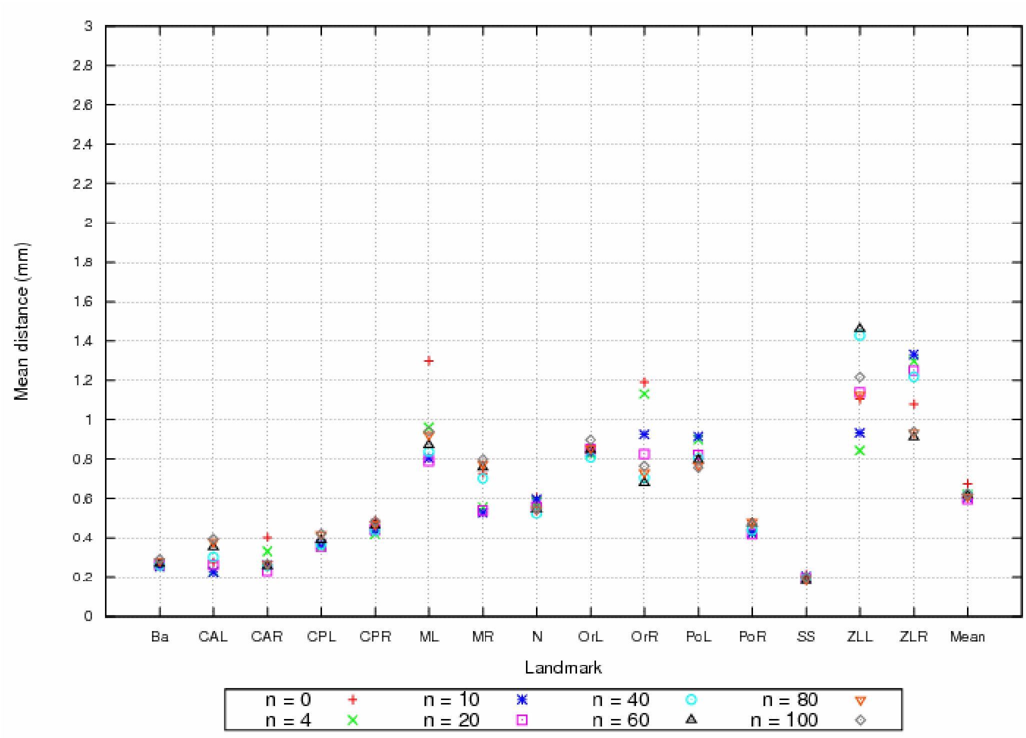

Figure 3. Mean distance between the pre- and postoperative landmarks (n=number of smoothing iterations).

4. DISCUSSION

From Table 2 it can be concluded that the low-pass filter and subdivision algorithm allow improving the surface quality without significantly changing the dimensions of the geometry. Figure 2 shows that the mean distance between the landmarks calculated without and with smoothing increases with a higher number of smoothing iterations. For some landmarks, however, even applying a low number of smoothing iterations may have a considerable impact on the coordinates (e.g. 10 iterations, mean distance above 0.5 mm for 4 landmarks). When evaluating the mean distance between the pre- and postoperative points (Figure 3), a significant variation between the landmarks can be observed. For some points, the effect of smoothing on the mean distance is small (e.g. Ba, SS), while for other points a larger variation in the mean distance can be observed for different numbers of smoothing iterations (e.g. OrR, ZLL). In general, the impact of smoothing the surface region is rather small for saddle-shaped structures (e.g. Ba, N, OrL, PoR), since the interpolation with natural cubic splines assures that a smooth line region is generated. Some points perform better with a higher number of smoothing iterations (e.g. CAR, OrR), while other points tend to perform less (e.g. MR).

These results indicate that no general conclusion can be drawn about the number of smoothing iterations. Applying a high number of smoothing iterations eliminates unwanted high curvatures from the model, but may also erase the characteristic features that define the landmark. The smoothing and subdivision operations are performed locally and therefore may not eliminate the geometrical differences resulting from the difference in image orientation and from the image resolution. Moreover, by calculating the landmarks as extreme points, a local extremity is identified, which in some cases may not represent the overall geometry of the anatomical structure. The use of a more global smoothing and surface interpolation or fitting could therefore have a positive effect on the reproducibility for different triangulated surfaces and will be investigated in future studies.

Several studies regarding the reproducibility of manual landmark identification have been performed. Recently, Olszewski et al. studied 13 skulls and 22 landmarks and reported mean intra- and interobserver distances (reconstructed mean log) of 1.210 ± 1.042 mm and 1.799 ± 1.037 mm for their 3D-ACRO analysis [7]. The values obtained in our previous and current study show that using a semi-automatic approach, higher reproducibility can be achieved. Nevertheless, significant variations were found between landmarks as well as skull models, which should be kept in mind when comparing pre- and postoperative data of patients treated with craniofacial surgery.

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