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The validity of using surface meshes for evaluation of three-dimensional maxillary and mandibular surgical changes.

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Short running title:

Surface meshes for evaluation of 3D hard tissue surgical changes

Key words: CBCT, surface mesh, surgical change, three-dimensional, 3D.

Summary

Three-dimensional changes of hard tissue position following orthognathic surgery have been reported using 3D cephalometry, changes in volume, centroid position and changes based on the surface model of the hard tissue. The aim of this study was to determine the validity of using surface models as a method of assessing positional changes of the maxilla and the mandible. The actual uni-directional movement of the maxilla (advancement or downgraft) and the mandible (advancement) together with bi-directional movement of the maxilla (simultaneous advancement and downgraft) were simulated on a plastic skull. Following CBCT scanning of each surgical simulation, the actual surgical movement was compared to the analysis based on surface model movement using the mean absolute distance of all the points, the 90th percentile and the RMS. All three methods of assessment of analysis consistency underestimated the actual amount of surgical movement. The movement was approximately one-third to one-half of the actual surgical movement. The use of surface meshes and point-to-point measurements grossly underestimates the 3D changes of the maxilla and mandible in simulated surgical procedures. Currently there are limitations in fully describe the true positional changes of the maxilla or the mandible in three dimensions.

Introduction

Orthognathic surgery involves correction of a dentofacial dysmorphology by repositioning the maxillary and mandibular bones into the pre-planned position with six degrees of freedom. This refers to the freedom of movement of a rigid body in three-dimensional space. The body is free to move anteriorly or posteriorly, superiorly or inferiorly, laterally or medially (translation in three perpendicular axes) combined with rotation about the three perpendicular axes, termed pitch, yaw, and roll respectively. The potentially complex positional changes of the maxilla and mandible required during surgery are presently determined by a combination of pre-operative model surgery planning,[1] two-dimensional (2D) photocephalometeric planning[2] or three-dimensional (3D) planning.[3]

Traditionally assessment of 2D maxillary and mandibular changes are determined by superimposing pre- and post-surgical lateral cephalograms on the anterior cranial base and changes in A-point and B-point, in the x and y directions calculated. These single anterior points are often used to describe the movement of the entire maxillary and mandibular basal bone. However the points are dento-alveolar and are considered unreliable as they are affected by surface remodelling and underlying tooth position.[4] Post-operative skeletal position should rely on basal bone assessment as any post-operative dental changes may camouflage the true basal bone position. Therefore clinical or 2D radiological assessment of teeth position may not accurately reflect basal bone changes.

Three-dimensional changes of hard tissue position have been reported using 3D cephalometry,[5] changes in volume,[6] change in centroid position[7] and changes based on the surface model of the hard tissue.[8] Measurements using 3D cephalometry are a natural progression from conventional 2D cephalometry and rely on landmark identification on a 3D surface model. Even though the assessment is relatively accessible using commercial software, the same problems with surface remodelling and changes due to underlying tooth position are still present. There maybe additional errors generating the 3D surface from the DICOM data and subsequent landmark identification.[5] The previously reported methods of volume changes or changes in centroid position do not adequately describe changes in basal bone position. For instance a change in volume does not quantify directional or magnitude measurement and changes in the centroid position of a shape i.e. the maxilla or mandible, does not describe complex 3D positional changes. A common method of assessing changes of 3D surfaces involves measuring the point-to-point distance of one mesh (the pre-intervention model) to the second mesh (post-intervention model) and generating a colour distance map. The main disadvantage with this technique is that the point-to-point measurement is the distance between two nearest points rather than the same corresponding points on the two surfaces. This has recently been explained for quantifying changes in soft tissue.[9] Given this problem. this raises the question whether the use of surface models to assess 3D skeletal changes is a valid method of assessment? Especially given the complex morphology of the maxilla and mandible, greater magnitude and variation in the direction of movement of the hard tissue compared to soft tissue changes.

Therefore the aim of this study was to determine the validity of using surface models as a method of assessing positional changes of the maxilla and the mandible as a result of simulated surgery.

Materials and methods

A Le Fort I osteotomy was performed on a plastic skull. Prior to the osteotomy a locating plate was constructed from acrylic that allowed the maxilla to be returned to its original position. The skull was mounted onto an adjustable universal joint which was secured to a 2cm thick Perspex base. An adjustable stage from a defunct microscope was placed below the maxilla; between the stage and maxillary occlusal plane there was a height adjustable platform. Once the maxilla was secured to the platform this arrangement allowed only 2 degrees of freedom of movement of the maxilla i.e. anteriorly or posteriorly and superiorly or inferiorly; any pitch, yaw, roll and lateral or medial movements were restricted. Using a Denar slidematic facebow (Whipmix, Louisville, KY) with a spirit level the skull was oriented and secured so the Frankfort plane and inter-auricular plane were horizontal; the skull assembly was conebeam CT (CBCT) scanned using 0.4mm resolution and 22cm Extended Field of View (iCAT, Imaging Science, Hatfield).

The maxilla was secured to the platform using sticky wax and removed from the skull base, using the adjustable stage the maxilla was advanced in 3mm increments and downgrafted in 2mm increments. An approximate magnitude of movement was determined using Vernier calipers positioned parallel to the path of movement of the maxilla. Following each maxillary movement the skull was CBCT scanned using the protocol previously described, Figure 1. In total 4 separate downgraft, 11 separate advancement and 12 combined downgraft and advancement procedures were simulated for the maxilla.

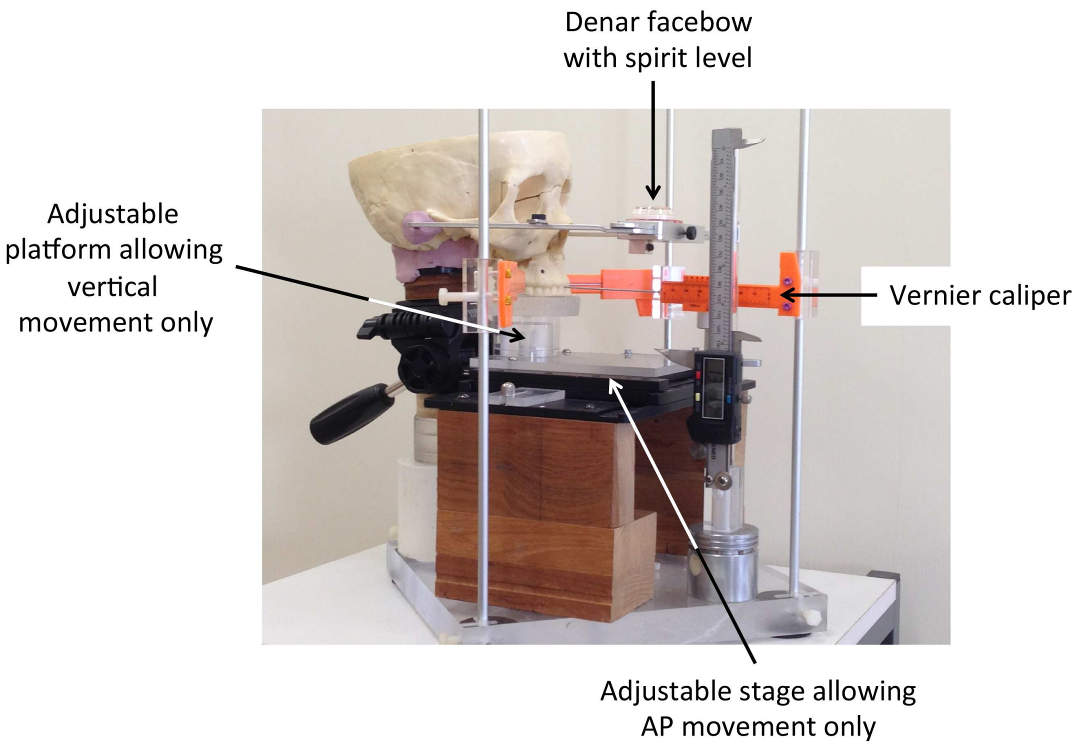

Figure 1 Experimental set-up for simulated surgical movements.

The data processing pipeline is shown in Figure 2. Following CBCT scanning all the DICOM scans were converted to surface mesh images using MeVisLab (MeVis Medical Solutions Ltd., Germany) and saved in STL format. Using rigid registration and the iterative closest point (ICP) algorithm, the baseline scan and each of the maxillary movement scans were superimposed onto the skull base maintaining the baseline image position using VRMesh (Seattle City, U.S.A.) and saved in the new aligned 3D position. Since the skull was correctly oriented during the CBCT scan it was possible using Minimagics software (Materialise, Belgium) to create a profile, passing through the sagittal

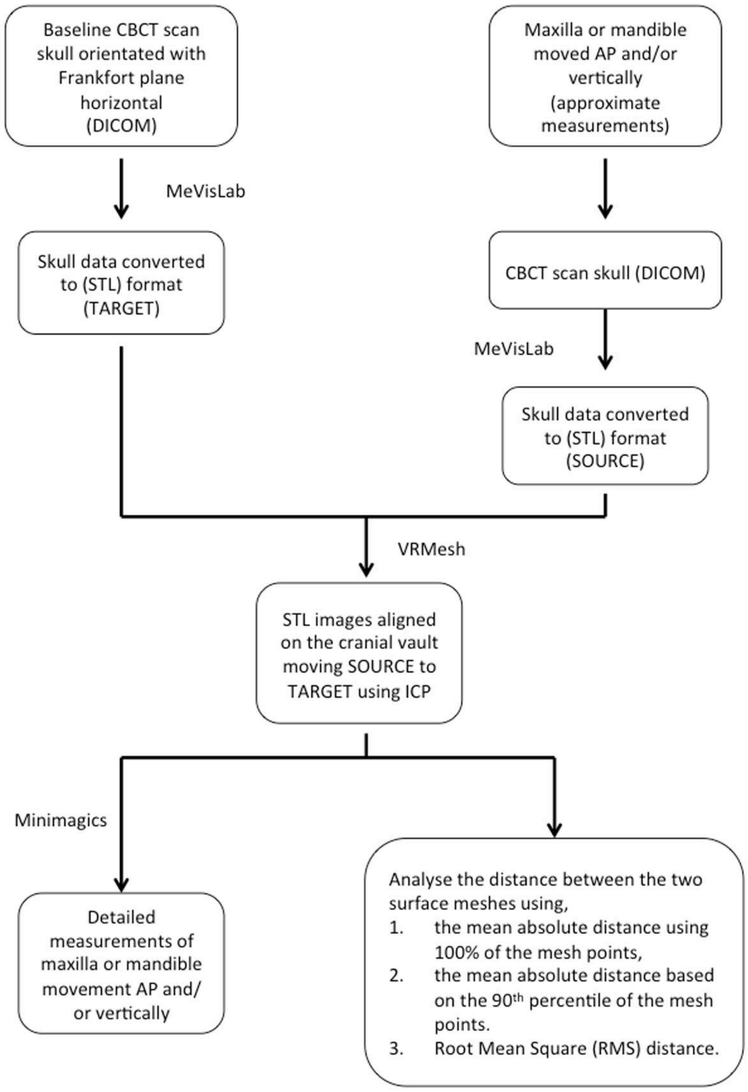

Figure 2 Data processing pipeline

plane, of the two superimposed images. Horizontal and vertical changes in the maxillary position were measured, Figure 3.

A similar procedure was carried out for the mandible. Following each advancement the mandible was secured to the maxillary dentition using sticky wax and CBCT scanned using the same scanning protocol. The same software pipeline was used to determine the horizontal changes of the mandible at each of the 4 advancement increments.

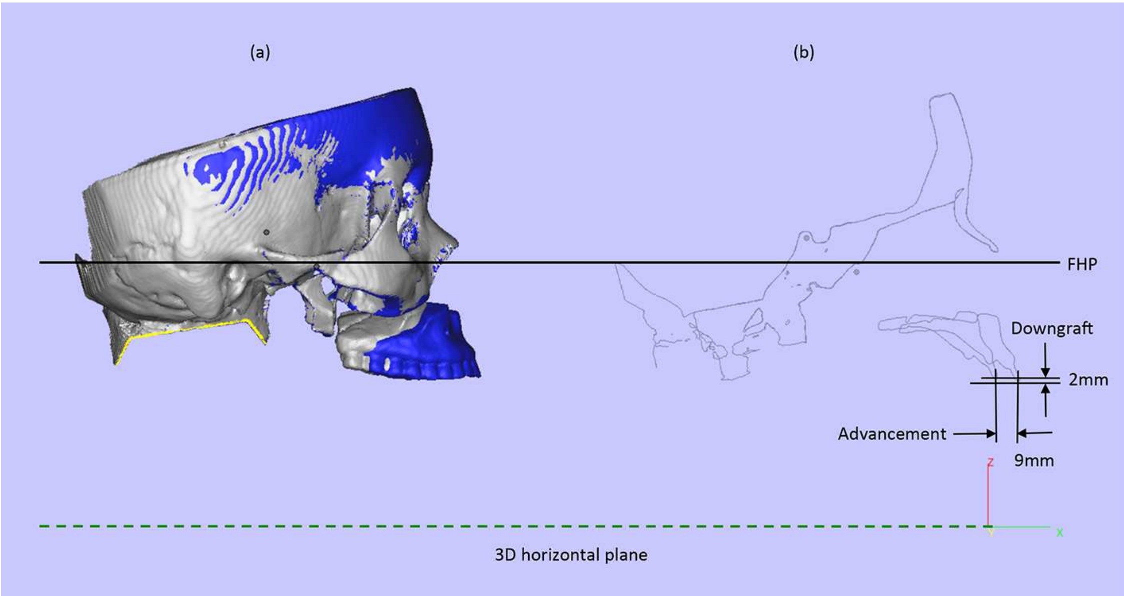

Figure 3 Measuring actual horizontal and vertical changes in maxillary position, (a). 3D surfaces models superimposed on cranial base, baseline model (silver) and 9mm advancement and 2mm downgraft model (blue), (b). Horizontal and vertical changes in maxillary position based on a profile, passing through the sagittal plane of the two superimposed images.

Error Study

To assess the reproducibility of the method, the superimposition and maxillary and mandibular movements were re-measured for 5 random surgical movements after 4 weeks later. Using a Students *t*-test and coefficient of reliability the systematic and random error were assessed.

Analysis

The results of the error study showed there was no systematic error ($p=0.56$) or random error ($r=0.99$) and the maximum error between readings was 0.2mm.

Each pair of aligned baseline and simulated surgical 3D models were imported into VRMesh and both the skull images were deleted leaving only the maxilla or mandible, Figure 4. For each simulated surgical movement three methods were used to analyse the distance between the two surface meshes, the mean absolute distance using 100% of the mesh points, the mean absolute distance based on the 90th percentile of the mesh points and the Root Mean Square (RMS) distance. The mean 90th percentile was determined by arranging the absolute distances between the two surface meshes for 100% of the mesh points in descending order and then calculating the mean of the lower 90th percentile. The RMS distance was calculated by squaring the absolute distances of 100% of the mesh points between the two surface meshes, averaging the squares, and then taking the square root.

Results

Maxillary advancement

All three methods of assessment consistently underestimated the actual amount of maxillary advancement; the larger the actual movement, the greater the underestimation. The calculated maxillary advancement was approximately 33%, 26% and 42%, of the actual advancement using the mean absolute distance of 100% of the mesh points, the mean absolute distance based on the 90th percentile of the mesh points and the Root Mean Square (RMS) distances respectively, Table 1.

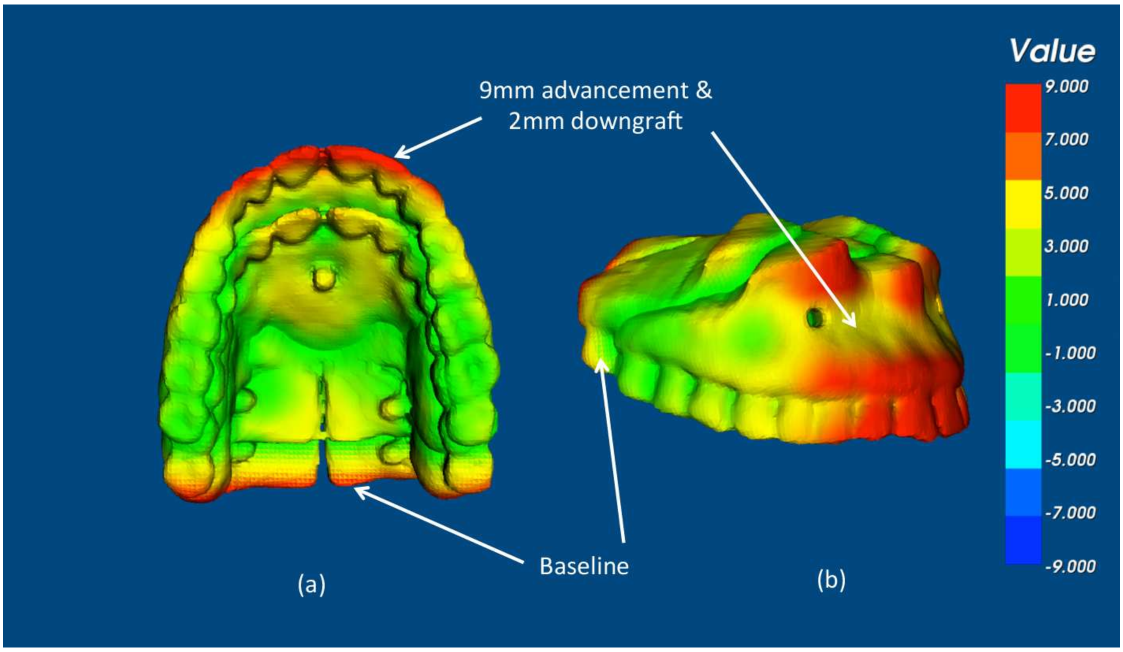

Figure 4 Using VRMesh the skull images were deleted leaving only the maxilla and the difference between the two surfaces determined based on an colour distance map, (a). occlusal view and (b). bucco-labial view.

Maxillary downgraft

All three assessment techniques again underestimated the actual downgraft actually carried out.. The calculated maxillary downgraft was approximately 50%, 40% and 50%, of the actual advancement using the mean absolute distance of 100% of the mesh points, the mean absolute distance based on the 90th percentile of the mesh points and the Root Mean Square (RMS) distances respectively, Table 1.

Maxillary downgraft and advancement

Since this was a bi-directional movement, the "net" change in the actual maxillary position was described as a vector of displacement. For example if the maxilla moved down 3mm and advanced 4mm the vector of displacement was calculated at 5mm.

The actual amount of maxillary movement was underestimated by approximately 30%, 30% and 40%, of the actual advancement using the mean absolute distance of 100% of the mesh points, the mean absolute distance based on the 90^{th} percentile of the mesh points and the Root Mean Square (RMS) distances respectively, Table 2. In all cases the largest differences were observed with the largest simulated movements.

Mandibular advancement

The absolute mean distance was approximately 41% and 36% of the actual advancement using the mean absolute distance of 100% of the mesh points and the mean absolute distance based on the 90^{th} percentile of the mesh points respectively. The RMS measurement was approximately half of the actual amount, Table 3.

Discussion

This study was undertaken to determine the validity of using mesh surface data generated from CBCT data to quantify the magnitude and direction of hard tissue change using a simulated model. It was not possible to conduct this study on actual data as the exact hard tissue changes produced are not quantifiable due to peri-operative surgical error, relapse, dental movement and bone surface remodelling.[10] Therefore a plastic skull was used to simulate the various surgical movements. Unfortunately it is not possible to compare the results of the present study with previous studies. Since previous studies have utilised surface meshes to quantify pre-operative and post-operative differences to determine the surgical change in patients when it is unknown i.e. the method was assumed to be valid. The aim of this study was to determine the validity of that assumption.

Complex dentofacial deformities are three dimensional in nature and so 3D planning and movement of the underlying skeletal hard tissue is necessary. Currently CBCT is the favoured method to image the hard tissue. The image obtained can be visualised in many ways; viewing the slice data, direct volume rendered 3D model and 3D surface model rendering. The easiest, most clinically useful and least computational intensive is 3D surface model rendering, resulting in production of a polygonal mesh. The mesh is comprised of points or “vertices” with known 3D co-orientates.

Previous studies have used the colour distance mapping method to assess 3D hard tissue displacement.[8, 11-14] These colour maps are qualitative methods of visualising quantitative changes in skeletal position. Generally a green colour indicates zero change, warmer (red) colours positive changes and colder (blue) colours negative change. These measurements are obtained by the “nearest point-to-point” distance of one surface from the other. The points are not corresponding anatomical points but the two nearest points. The operator then sets a threshold value and a "colour map" is generated with each distance being assigned a specific colour. This method of analysis grossly illustrates the direction and magnitude of movement but cannot describe complex 3D movements. Also any erroneous data due to deflects in the surface mesh will become immediately apparent. To overcome these problems methods of creating anatomical correspondence between the two images have been reported.[15] However the software pipeline is complicated and time consuming and so far has only been reported on the mandible. The end result however is still a single linear measurement to describe a 3D change together with a colour map and vector arrows showing the direction of change of the corresponding landmark.[15,16]

Some studies have used "isolines" to "quantitatively measure the greatest displacements between points in the 3D surface models". [12,17,18] This again provides only one reading of the largest difference between two surfaces. Any erroneous data however on the surface mesh for example streak artefact or surface roughness will have a marked effect on this distance. This is the reason for not generally using 100% of the surface mesh, during soft tissue analysis, but to use the 90th percentile of the distances in an attempt to avoid incorporating outlying data in the analysis.[19] Using only the 90th percentile of the data however reduces the mean absolute distance between the two surfaces and will automatically result in underestimation of the distance. This is the case in this study; since there were no outlying data points using the 90th percentile of data markedly reduced the distance. Whereas using 100% of the data has the potential to overestimate the distance, but again as there are no outlying data points the measured distances were greater than the 90^{th} percentile distances but less than the actual distance measurement. It should also be appreciated that any physiological bone surface remodelling will directly affect the surface model topography.

For the analysis of pure downgraft movement the mean absolute error grossly underestimated the actual movement and approximately only 40-50% of the true displacement was measured. This is because the points parallel to the direction of movement will “slide” past one another and a new point will replace the previous point i.e. the distance between the two surfaces will not have changed according to the nearest point analysis i.e. buccal and lingual surface of teeth during maxillary downgraft. True separation of the two surfaces however will only occur in the palate and occlusal surfaces of the teeth, this is where the true displacement is correct. However the areas of little or no change will bias the larger readings reducing them in size. Clinically this maybe further exaggerated since the teeth are often in occlusion during the scan and so cannot be used. Any metallic appliances will cause streak artefact and erroneous data and the palatal vault hard tissue is often poorly converted and imaged during scanning. This makes the use of surface models to measure downgrafts difficult.

For advancement procedures, maxillary and mandibular, the opposite holds true with the points in the direction of the advancement i.e. horizontal portion of hard palate and occlusal surfaces of posterior teeth give the impression of no movement, but areas such as the labial surface of the incisors will show the largest movement, Figure 4. However it is these surfaces that are more like to be distorted due to appliances, streak artefacts or the effects of beam hardening. The same problem of basing the analysis on the mean reduces the measurements.

The complexity of measuring bi-directional movements can only really be addressed by considering the vector of the anticipated movement of the points. Using the mean absolute values now becomes even more difficult since the analysis will use the nearest point that is hard to determine. This is reflected in the gross underestimation of the mean absolute distance and the RMS value.

No roll, pitch or yaw movements were incorporated in any of the surgical simulations since the points of one mesh would slide past one another and the net measurement effect would be zero. Introduction of yaw into the surgical simulation is also difficult and would confound the problem hence it was not included. This study used only two of the six degrees of freedom, AP and vertical change, to simplify the analysis, but even then the three chosen methods of analysis were unable to accurately reflect the actual movement. By introducing all six degrees of freedom of movement none of the three common methods of analysis would not be able to measure the actual change.

The type of movement of the maxilla and mandible performed during this study in mathematical terms would be described as a “rigid body transformation"; this implies that all the points with in the structure maintain a constant relationship. The maxilla can translate whilst maintaining its orientation but it can also change its orientation but maintain its location. No single linear measurement can quantify these complex movements. The single numerical values obtained in this study and previous studies are the Euclidean distances between points. These give no indication of direction but taken into account with the colour map some additional information can be obtained. The use of vectors, which describe magnitude and direction maybe a potential solution[16] but again fully describing differential hard tissue in three dimensional space may always prove difficult. Translation into a clinical arena may prove even more difficult.

The use of 3D imaging has revolutionised dentistry especially with respect to visualising position of impacted teeth, root resorption and implant placement.[20] The location, position and linear distances of adjust structures is readily achievable using on-screen measurements tools, however the complex multidirectional movement of skeletal structures is readily visualised but difficult to quantify in a clinically useful and valid manner. Interestingly when assessing changes in the hard tissue position following clinical intervention linear measurements using standard cephalometric measurements are still used. This under utilises the 3D information obtaining as a result of volumetric or surface scanning and questions the need for 3D images. If the patient is going to be exposed to additional radiation the benefit must out way the risk and the maximum information should be obtained. Currently we are not in a position to quantify hard tissue movement using the current surface mesh analysis techniques. Hopefully with time new types of analysis will become available to solve this problem, until then the disadvantages of the current methods should be taken into account when trying to assess 3D hard tissue change.

Conclusions

The use of surface meshes and point-to-point measurements grossly underestimates the 3D changes of the maxilla and the mandible in simulated surgical procedures. The use of anatomical correspondences is a possible alternative method but should also be viewed with caution. Currently it is difficult to fully describe the true positional changes of the maxilla or the mandible in three dimensions.

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Table 1 Absolute mean difference (100% and 90th percentiles), standard deviation and RMS distances between the actual simulated uni-directional surgical movement of the maxilla and the 3D surface.

Surgical movement (mm)		100% of points		90th percentile		RMS
Advancement	Downgraft	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	(mm)
-	2.1	1.1	0.7	1.0	0.5	1.3
-	3.6	1.8	1.1	1.6	1.0	2.0
-	5.9	2.6	1.8	2.3	1.5	3.2
	8.5	3.4	2.3	3.0	2.0	4.1
2.7	-	1.1	0.9	0.9	0.7	1.4
2.9	-	0.8	0.7	0.7	0.5	1.0
3.3	-	1.1	0.9	0.9	0.7	1.4
3.7	-	1.2	0.9	1.0	0.7	1.5
5.6	-	2.0	1.7	1.6	1.3	2.6
5.8	-	1.7	1.5	1.4	1.1	2.2
6.3	-	2.0	1.7	1.6	1.3	2.6
6.6	-	2.1	1.7	1.7	1.3	2.7
8.5	-	2.9	2.5	2.3	1.9	3.8
9.0	-	2.8	2.4	2.2	1.9	3.6
9.3	-	2.8	2.3	2.2	1.8	3.6

Table 2 Absolute mean difference (100% and 90th percentiles), standard deviation and RMS distances between the actual simulated bi-directional surgical movement of the maxilla and the 3D surface.

Surgical movement (mm)		Vector (mm)	100% of points		90th percentile		RMS
Advancement	Downgraft		Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	(mm)
2.7	1.8	3.3	1.2	0.7	1.1	0.6	2.3
5.6	1.8	5.8	1.8	1.1	1.5	1.0	2.1
8.5	1.7	8.7	2.5	1.7	2.1	1.4	2.9
2.9	3.8	4.7	3.1	2.2	2.7	1.8	3.8
5.8	4.0	7.1	1.9	1.4	1.6	1.0	2.3
9.0	3.7	9.8	2.2	1.5	1.8	1.2	2.6
3.3	6.0	6.8	2.6	1.8	2.3	1.5	3.2
6.3	6.0	8.7	3.2	2.2	2.7	1.8	3.8
9.3	6.1	10.8	2.8	2.3	2.4	1.7	3.6
3.7	7.9	8.9	3.0	2.2	2.4	1.7	3.6
6.6	7.7	10.2	3.2	2.3	2.7	1.8	3.9
9.3	7.5	11.9	3.4	2.4	2.9	1.9	4.1

Table 3 Absolute mean difference (100% and 90th percentiles), standard deviation and RMS distances between the actual simulated surgical advancement of the mandible and the 3D surface mesh.

Surgical movement (mm)	100% of points		90th percentile		RMS
Advancement	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	(mm)
3.6	1.6	0.9	1.4	0.8	1.9
5.5	2.3	1.4	2.0	1.2	2.7
7.3	2.9	1.9	2.5	1.6	3.5
8.9	3.5	2.4	2.9	1.9	4.2