The Op-Track: a computer-aided maxillary repositioning device

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Abstract

Introduction
This pilot study was designed to evaluate the reproducibility of safety glasses in relocating the maxillary position, thus acting as an external reference point for orthognathic surgery as well as to introduce a new non-invasive computer-aided technique to control the intra-operative repositioning of the osteotomized maxilla in three planes.

Materials and methods
Twenty volunteers were recruited and divided into two equal groups. Group 1 was subdivided to validate the accuracy of safety glasses in a sitting and supine position. The three-dimensional maxillary repositioning system was then authenticated by distributing Group 2 in a similar manner. Finally, the three-dimensional system was tested on the skull (model) surgery. Computer readings were compared with manual (digital calliper) ones.

Results
The validation of safety glasses revealed a coefficient of repeatability in the range of 0.052–0.42 with no significant differences between the results in the sitting and supine position. The subjects in Group 2 had similar results with greatest variations in the z (vertical) axis. The coefficient of repeatability range (0.06–0.27) for the skull (model) surgery was very encouraging.

Conclusion
From our results, we can conclude that our three-dimensional maxillary repositioning system will be an invaluable tool for obtaining high accuracy in tracking maxillary movements during surgery.

Introduction
The most vital purpose of orthognathic surgery is to achieve the planned prediction tracing and model surgery in the patient during the operation and to maintain stable results post-operatively. The key to success in orthognathic surgery is the incisor–lip relationship, as the main concern of the patient is the aesthetic one1. The control of the maxillary position during Le Fort I surgery is the most important part of the procedure in terms of accuracy and stability2,5. In 1985, a technique of the maxillary movement with Le Fort I osteotomy was described based on the measurement of the distance between two reference points: a fixed superior point in the soft tissue nasion (a suture placed horizontally) and a point on the maxillary central incisor tooth. The technique could be used to corroborate direct bone measurements for the assessment of maxillary repositioning at virtually any time during the surgical procedure4. Van Sickels et al.5 demonstrated that an external reference point could more accurately achieve the maxillary central incisor position. Others have concluded that there is no significant difference between the results obtained using external vs. internal reference points (IRPs) in the positioning of the maxilla in the horizontal plane on Le Fort I cases6. Several authors have used external reference points such as a bone mark in the region of the glabella to the incisal edge7, nasion7, Kirschner pins8 and medial canthus9, and IRPs10 or the conventional internal reference lines in the lateral walls of the maxilla1 to measure the maxillary vertical repositioning. An intensive study was published to quantify the errors resulting from using different reference lines and points, showing more errors in internal reference lines11. Additionally, methods included an external three-point calibrator12, a maxillary measuring appliance (MMA)13, a modified type of face-bow14 provided with an inter-occlusal splint15, sandwich splint16 and three-dimensional (3D) double splint method combined with a surgical face-bow6 and an intermediate splint17. However, none of the studies mentioned the inaccuracy that could result from using the mandible as a guide for horizontal repositioning. The current protocols for repositioning of the maxilla in orthognathic surgery are as follows:

• Radiographic evaluation with the aid of the orthopantomograph and lateral cephalogram, confining the image of the maxilla and mandible to a two-dimensional (2D) plane.
• Reference points used intra-operatively are not adequate for the assessment of the maxillary position in a 3D plane.
• Transfer of the predicted model surgery onto the patient during surgery using occlusal wafers amounts to a significant amount of errors.
• Mandible is used as a guide for horizontal repositioning of the maxilla, which proves to be less accurate.

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accurate as the position of the condyle in the glenoid fossa cannot be assessed.

This study was conducted at the University College London (UCL) Eastman Dental Institute to evaluate the reproducibility of disposable safety glasses in relocating the maxillary position, thus assisting the surgeon in monitoring the movements performed on the maxilla after plating the osteotomized maxilla.

Materials and methods

A total of 20 volunteer subjects were recruited for the entire study; all of them were fit and healthy and could attend the different stages of the study. Subjects with obvious facial asymmetry were excluded. All the volunteers were asked to sign a written consent form to confirm their participation in the study. The clinical study was approved by the EDI/EDH Joint Research and Ethics under JREC application number 99/E027. The subjects were divided into two equal groups. Group 1 was used to validate the accuracy of safety glasses in a sitting and supine position. The 3D maxillary repositioning system (Op-Track) was then authenticated by distributing Group 2 in a similar manner.

Safety glasses

Plastic safety glasses (Bollé®, no. 1F-EN 166-F, France) were used along with a pair of Velcro® hook-and-loop straps attached to the ear pieces to withstand the forces applied during impression taking and manipulation through different measurements. Using a 0.5-mm-round bur, a hole was drilled on the glasses in an area representing the nasion (in the middle of its frame) that was used for the measurements. Impressions of the nasal bridge and forehead extending just below the supraorbital ridge (eyes closed) were taken using a condensation-cured polysiloxane elastomer (Coltène®, Switzerland) along with the safety glasses as its delivery system. An electronic digital calliper (0–150 mm) with a measuring speed of $\leq 1.5$ m/s was calibrated before use to ensure the maximum accuracy of the measurements.

Validation of the safety glasses

Ten subjects were analysed in the sitting and supine position (Group B). For each subject, an impression was taken and the distance between the hole made on the glasses and the middle of the incisal edge of the upper left central incisor was recorded. Four measurements were taken on each visit: the first two were named Test 1 (sitting) and the second two were named Test 2 (supine). After each measurement, the glasses were completely removed from the subject’s head and replaced. A total of 20 records were collected for each subject over five visits. All the records were analysed using a Microsoft Excel spreadsheet. The following statistical analyses were performed: mean of Test 1/Test 2, differences between Test 1 and Test 2, standard deviation (SD) of the differences and coefficient of repeatability (CR), which equals $2 \times$ SD of the differences.

The Op-Track

We developed a new computer-aided maxillary repositioning system (Op-Track) for assisting intra-operative positioning of the osteotomized maxilla based on the preoperative planning. The web camera, which views the target, must be securely mounted on the object that acts as the frame of reference for the measurements of the movements. The system is tolerant to normal ambient lighting. The default measurements are in the coordinate frame of the camera’s charge-coupled device (CCD), the $x$ and $y$ axes on the CCD plane and the $z$ axis normal to it. The software allows for the setting of a reference position so that calculations can be made in the frame of reference of the target position at the start of the process. Since the target is mounted in alignment with the occlusal plane of the teeth, it allows the movements to be related to the initial and intended positions of the teeth.

The components of the Op-Track are as follows:

- Camera (Figure 1) used was a Philips ToUCam 740 CCD webcam (640 x 480 pixels). It accommodates a ball-and-socket joint to enable secure and adjustable mounting. A screw holder allows the camera to be fixed onto the glasses. The camera was plugged into the USB socket on the personal computer (PC) running the tracking software and the camera obtained its power from the PC.

- Target/light source (Figure 2) was designed to emit a precisely controlled pattern of light spots powered by a small 6 V battery, thus catering for several hours of continuous use. The spots are bright red on a matt-black background to maximize the contrast and were designed to radiate a wide beam of uniform light so that the rotation of the target has a minimal effect on the observed spot.

- Tracking software was written in C to run on Windows XP. Images are collected from the camera and analysed to determine the position of the target. The software provided the operator with the following data: (a) angle of the maxillary movements on the sagittal, coronal and axial planes; (b) distance of the maxilla from the camera in the three planes ($x$, $y$, $z$).

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and $z$; (c) position of the left molar, right molar and central incisors in relation to the camera in the three planes ($x$, $y$ and $z$) (Figure 3). The software can be set to give a mean reading of 10, 30, 50 and 100 captures, with distances given in mm and angles in degrees; the software also gives the variance of three angles and three distances in separate columns. To obtain the position of the molars and central incisors in relation to the camera, the system was provided with the dimensions of the wafer by measuring the distances between the upper left and right molars (mesiobuccal cusps) and the mid-central incisors point in three dimensions from the light source. These numbers were saved in a specific file on the hard disk before starting the program.

- Occlusal wafers were constructed for each subject to retain the light source. Maxillary impressions using dental alginate were taken for each subject and wafers were constructed from a quick, high-impact acrylic resin with bilateral ball-ended clasps on the upper first premolar and first molar to enhance maximum retention to the maxilla throughout the measurement procedures.

A square stainless-steel tube (30 mm in length) was fixed to the wafer anteriorly, perpendicular to the mid-central incisors point, and was used to accommodate the 15 mm probe of the light source (Figure 4).

- Modifications of the safety glasses (Figure 1) were made by placing a stainless-steel screw (15 mm in length and 6.2 mm in diameter) on the middle of the glasses (nasion point) with the help of a rapid-cure acrylic resin, onto which the camera was fixed.

**Validation of the Op-Track**

Ten subjects were recruited and divided into two groups of five: Group A was assessed in a sitting position and Group B in a supine position on the dental chair (Figure 5). After connecting the camera to the computer, the safety glasses were secured on the subject’s head with the Velcro® straps. The wafer was then placed on the subject’s maxillary teeth. The program was then left to run for 10 s for each measurement. First, the position of the maxilla in relation to the web camera was recorded, which is considered as the reference for subsequent measurements. Ten measurements were taken, with the glasses being removed and replaced after each measurement. The output was saved in a folder on the hard disk. Because of the huge amount of numbers obtained from the software, we recorded the maximum and minimum differences from the reference set of measurements for the three angles and three distances in the three planes ($x$, $y$ and $z$). All results were exported to a Microsoft Excel spreadsheet for analysis.

Finally, the following statistics were calculated: mean of the differences from the reference set of measurements, standard error of mean (SEM) and SD.

A skull was mounted on a wooden platform for simulating the patient’s position on the operating table. A maxillary impression was taken to construct a surgical wafer. A second impression was taken for the bony nasal bridge and the forehead using hard wafers. To this end, an acrylic resin (rapid-cure acrylic resin) was used to construct a surgical wafer. Finally, the following statistics were calculated: mean of the differences from the reference set of measurements, standard error of mean (SEM) and SD.

**Figure 1: Web camera with ball-and-socket joint**

**Figure 2: The target light source**
the safety glasses. Using the Op-Track, we recorded the preoperative position (reference position). After recording the initial readings, the system was then removed from the skull. An electrical saw was used to osteotomize the maxilla at the Le Fort I level, and then four (10 mm) screws were placed on each side of the maxilla below and above the osteotomy line. This facilitated the retention of the osteotomized maxilla (using fine elastics) between the readings of each movement of the maxilla. The camera was then placed on its position on the skull and the surgical wafer fixed on the maxilla (Figure 6). The maxilla was then moved in one direction and the new position was retained using sticky wax and fine elastics on the screws. The digital caliper and the Op-Track

**Figure 3:** The main software screen

**Figure 4:** Occlusal wafer with ball-ended clasp
were used to measure the amount of movements in relation to the pre-operative readings (reference position). Five measurements were recorded for each axis (x, y and z) from three points on the osteotomized maxilla (right first molar, left first molar and mid-central incisors point) following each movement. To validate the Op-Track, the readings were compared with those of the digital calliper. Again, the mean of the differences, SD and CR were calculated.

Results
Safety glasses
The analysis was performed to evaluate the differences in the readings when changing the subject’s position (sitting and supine). Here, the mean values of the measurements in the supine and sitting position have been considered for each of the 10 subjects along with the differences between the two mean values. The minimum value was −0.022, corresponding to subject number 4, and the maximum value of the difference was 0.024, corresponding to subject number 5 (Figure 7). The overall accuracy of the safety glasses in relocating the maxillary position is considerably
good; the SD was not more than 0.017 in both the sitting and supine positions. Figure 8 shows the results of the CR test for the 10 subjects used in this part of the study. The minimum value was 0.052, corresponding to subject number 4, and the maximum value was 0.42, corresponding to subject number 1. Ninety-five per cent of the repeated measurements were located within a range of value ± CR. The CR also showed that the errors are less than a maximum of 0.5 mm.

The Op-Track
Due to the repeatability of data output collected from each subject, only the minimum and maximum values of differences from the reference position were considered for each axis (x, transverse; y, anteroposterior; z, vertical; Table 1). Further analysis of these results revealed the mean of the minimum and maximum differences from the reference position. Finally, SEM was calculated for each axis (x, 0.247; y, 0.247; z, 0.254).

Application of the Op-Track on the skull (model) surgery
All measurements and results were based on differences in the readings between the digital calliper and camera (Table 2). The statistical analysis included the mean of the differences, SD and CR in the x, y and z planes for the central incisor, left upper molar and right upper molar.

Discussion
There is a general agreement that the IRPs are not only non-

Table 1 Range of the differences from the reference position and mean (mm)

<table>
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<th>Subjects</th>
<th>x axis</th>
<th>y axis</th>
<th>z axis</th>
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<tr>
<td></td>
<td>Min</td>
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<td>Min</td>
</tr>
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<tr>
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<tr>
<td>Mean</td>
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Original research study
reproducible\textsuperscript{11,18} but also produce the highest errors among other reference points. Some of the external reference points are invasive and require an incision for the placement of the screw or K-wire in the nasion area, with a subsequent scar and possible aesthetic deficit\textsuperscript{1,19}. Other repositioning devices are dependent on mechanical means such as surgical face-bow\textsuperscript{14}, MMA\textsuperscript{13}, Model Positioning Device and sandwich splint\textsuperscript{16} for transferring the predicted model surgery to the patient in the operating theatre. Most of these systems are complex and have multiple screws and joints, thus increasing the possibility of errors due to metal elasticity, gravity and accidental loose screws.

Model surgery-dependent repositioning systems can easily transfer the errors from the model surgery phase to the operating theatre, though tremendous care must be applied to eliminate the errors during all the steps of model surgery and wafer construction.

The ability of most systems to control both vertical and horizontal dimensions is limited, so the need to combine more than one technique is mandatory to achieve good results\textsuperscript{11}. Our validation of the safety glasses revealed that the highest SD was 0.017 and highest CR was 0.42, which are considered to be very low and of no clinical significance. The clinical validation of the Op-Track also did not show significant errors, but some variations in the readings between the three planes (x, y and z) were noticed. The highest SEM of differences from the reference position was noticed in the z axis, which represents the vertical movements of the maxilla (0.25). The application of our system on the surgery (skull model) also gave very encouraging results: the maximum CR did not exceed 0.27, corresponding to the z axis of the central incisors, and the minimum CR was 0.062, corresponding to the x axis of the upper left first molar tooth.

Considering all disadvantages and limitations of the previous maxillary repositioning devices that have been introduced in the literature, we carefully designed our system in such a way as to provide the maximum possible accuracy in tracking the maxillary movements, and hence, to achieve optimal results for the whole maxillomandibular repositioning in orthognathic surgery. All components of our system have been tested in the laboratory separately and then as one unit. The geometry of the light source was designed in such a way as to be as small as possible and also manufactured from materials that can be autoclaved to eliminate the risk of infections. The web camera that we used is one of the best ones in the market in terms of resolution and accuracy.

**Conclusion**

We believe that the introduction of our system (Op-Track) will open new horizons in the planning and execution of orthognathic surgery, minimize the intra-operative errors of maxillary repositioning and also help in accurate follow-up of possible relapse.

**Abbreviations list**

2D, two-dimensional; 3D, three-dimensional; CCD, charge-coupled device; CR, coefficient of repeatability; IRP, internal reference point; MMA, maxillary measuring appliance; PC, personal computer; SD, standard deviation; SEM, standard error of the mean.

**References**


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