Orthognathic Examination and Treatment Planning

37

Jaime Gateño, James J. Xia, and David Alfi

This chapter covers evaluation and treatment planning for patients needing orthognathic surgery. Evaluation and treatment planning are two processes that are part of the approach used to care for patients. This approach has four sequential processes: evaluation, assessment, treatment planning, and treatment (Fig. 37.1). Evaluation is a structured process used to appraise patients; it begins with the patient encounter and ends with an assessment. It has three steps: history, physical examination, and evaluation of diagnostic test. Treatment planning is a process used to determine the details of treatment. It begins after the assessment and ends before the treatment.

These processes, routinely used in clinical practice, are commonly modified to meet the clinical needs. In this chapter we present the processes of evaluation and treatment planning, as they can be modified for orthognathic surgery. Knowing, with precision, what orthognathic surgery is and when it is indicated is a prerequisite for these modifications.

The term orthognathic is a compound word of Greek origin (*ortho*, straight; *gnathous*, jaw) meaning straight jaw. Thus, the term orthognathic surgery refers to surgery that is done to *straighten a jaw*. It entails cutting a jaw and relocating at least one of its segments. It is done to correct jaw *deformities*. Some of these deformities occur in utero and are present at birth, while others are acquired later in life. They result from many causes: genetic abnormalities, deformations, intrauterine disruptions, diseases, injuries, or abnormal function.

For a given patient, a jaw deformity can be the primary problem, or it can be secondary to disease, injury, or functional impairment. An example of a patient in whom the deformity is the primary problem is a woman with a familial history of mandibular prognathism that develops this condition during puberty. Examples of secondary deformities are a young man with an anterior open bite from condylar destruction caused by juvenile arthritis (a disease), a teenager with retrognathia and facial asymmetry caused by condylar fracture and TMJ ankylosis during childhood (an injury), and a patient with anterior open bite because of mouth breathing (functional impairment).

Orthognathic surgery is indicated when a patient has a jaw deformity. Yet the mere presence of a deformity is insufficient. In addition to having a deformity, it should be severe enough so that it cannot be camouflaged with a simpler treatment (e.g., orthodontics, genioplasty). Moreover, it has to cause impairment or comorbidity. The impairment can be one of appearance or one of function: mastication, speech, breathing, or socialization. Comorbidities, which are concurrent conditions related to the primary condition, may also be present. Examples of comorbidities associated with jaw deformities are obstructive apnea, TMJ derangement, and occlusal soft-tissue impingement.

Jaw deformities that require orthognathic surgery affect at least one of the geometric properties of the jaws:

- Size
- Position
- Orientation
- Shape
- Symmetry

Deformities of *size* occur when a jaw is too big or too small. The term *hyperplasia* indicates pathological enlargement and *hypoplasia*, failure to attain normal size. *Micrognathia* is a synonym of *mandibular hypoplasia* and *macrognathia* of *mandibular hyperplasia*. The terms *macrogenia* and *microgenia* also refer to size, macrogenia indicating large chin and microgenia small.

Abnormal jaw positions occur in all cardinal directions. *Prognathism* and *retrognathism* are deformities characterized by abnormal anteroposterior position. By convention, anteroposterior position is assessed in relation to the cranial base. Prognathism occurs when a jaw is too far forward and

J. Gateño (✉) · J. J. Xia · D. Alfi
Oral and Maxillofacial Surgery, Houston Methodist Hospital, Houston, TX, USA
e-mail: jgateno@houstonmethodist.org

A. M. Greenberg, R. Schmelzeisen (eds.), *Craniomaxillofacial Reconstructive and Corrective Bone Surgery*,
https://doi.org/10.1007/978-1-4939-1529-3_37

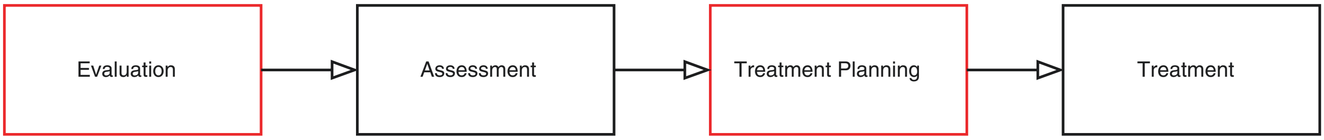

Fig. 37.1 Approach to patient care

retrognathism when it is too far backward. In the transverse direction, a jaw can be displaced, in either direction, away from the median plane, a deformity called *laterognathia*. Vertically, a jaw can be too far down—*excessive downward displacement*—or too far up—*deficient downward displacement*.

Malrotations occur when a jaw is abnormally oriented. They are classified according to the axis on which the abnormal rotation occurs. When a jaw is malrotated around the transverse facial axis, one says it has *abnormal pitch*. When it is malrotated around the anteroposterior axis, one says it has *abnormal roll*, a condition also known as cant. And when it is malrotated around the vertical axis, one says it has *abnormal yaw*.

Shape is that geometric characteristic of an object that is not size, position, nor orientation [1]. A jaw with abnormal shape is said be *distorted*.

The human face has reflection symmetry around one plane, the *median*. For facial symmetry to exist, two conditions must be met [2]. First, each of the units that compose the face must itself be symmetrical—a condition called *object symmetry*. Second, each of the units must be symmetrically aligned to the median plane—a condition called *symmetric alignment*. Jaws can have deformities of symmetry either because of object asymmetry or because of misalignment. The terms *mandibular asymmetry* and *maxillary asymmetry* refer to abnormalities in object symmetry, whereas the term *asymmetric alignment* is used to denote abnormal alignment that causes asymmetry.

The different types of jaw deformities (size, position, orientation, shape, and symmetry) are frequently correlated [2, 3]. For example, *asymmetric alignment* cannot occur in the absence of at least one other deformity: laterognathia, abnormal roll, or abnormal yaw. Figure 37.2 presents a mind map and the different dentofacial deformities.

Evaluation

Evaluation is a structured process that begins with the patient encounter and ends with an assessment. It has three steps: history, physical examination, and the appraisal of diagnostic studies. In the case of a patient with a jaw deformity, the end result of the evaluation (the assessment) should include:

- A primary diagnosis
- Secondary diagnoses and comorbidities, if present
- A statement of the severity of the deformity
- A list of impairments caused by the deformity

During the evaluation process, the provider should collect all data necessary for these assessments.

History

The history is the subjective part of the evaluation. It is obtained by interviewing the patient. It has several parts. They are:

- Chief complaint(s)
- History of the present illness
- Past medical history
- Review of systems

The chief complaint should describe the patient's main *symptoms* or *problems*. It should not be a statement of treatment "I need surgery." Examples of suitable chief complaints are "I have difficulty chewing," "my bite is off," and "my face is crooked."

The history of the present illness should answer the following questions:

- When did the deformity first become apparent and how did it evolve?
- Does the patient have chewing problems? When trying to ascertain this question, one should be specific on questioning patients. Many patients tend to answer no to the general question: do you have chewing problems? Yet they may answer in the positive when asked a more specific question like: can you cut food with your front teeth (i.e., incising)?
- Does the patient have breathing problems (e.g., mouth breathing, snoring, or witnessed apnea)?
- Does the patient have speech problems?
- Does the patient have social or emotional problems related to the deformity?
- Does the patient have other comorbid conditions? One should ask about TMJ symptoms (joint pain, joint noises, limited or abnormal motion), soft-tissue impingements, and other diseases that may affect the jaws.

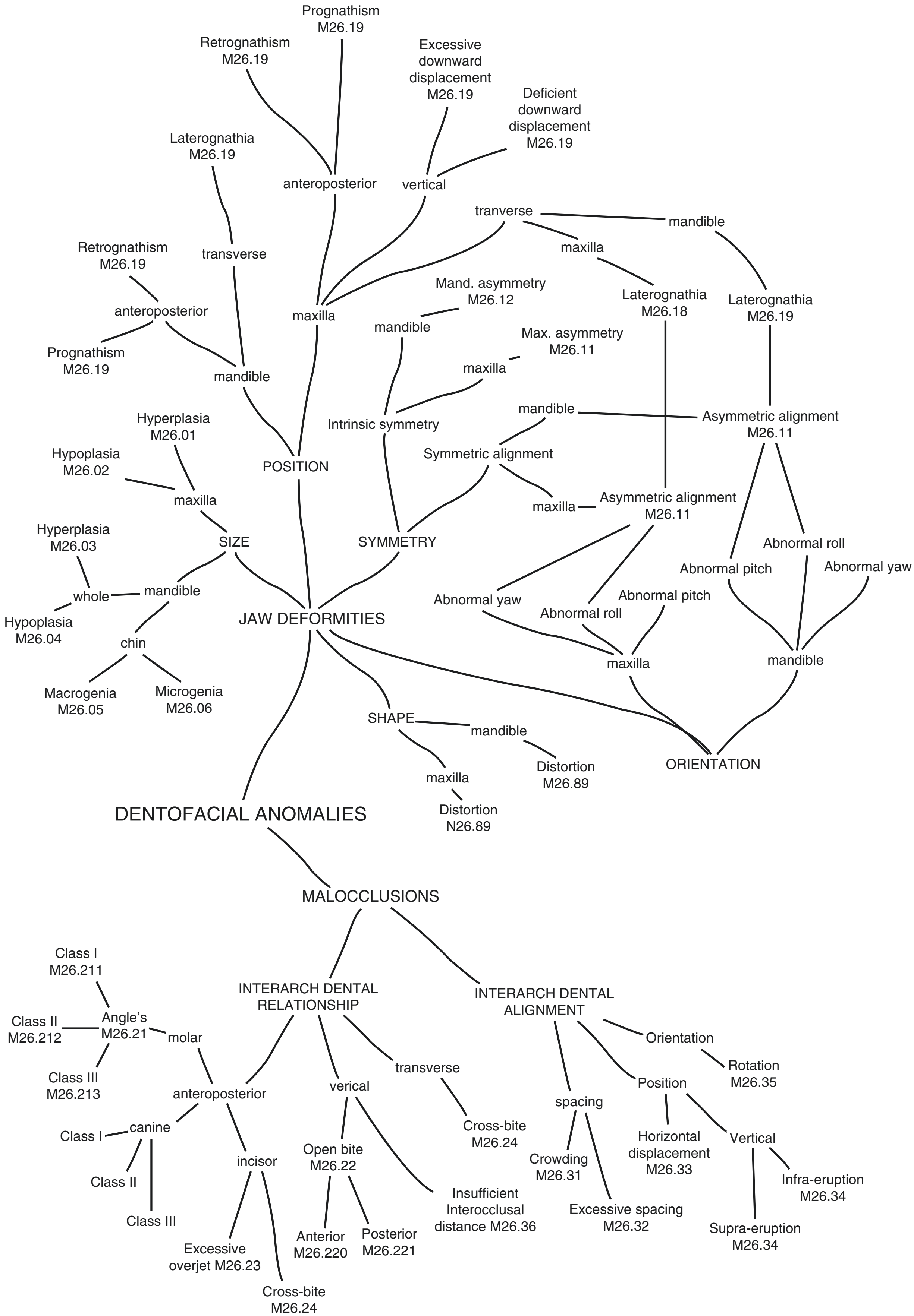

Fig. 37.2 Mind map of dentofacial deformities

Physical Examination

In this chapter the authors present a *problem-focused* physical examination aimed at evaluating jaw deformities. The examination is divided into two parts: an assessment of facial form and a cursory evaluation. The purpose of the first is to determine the presence, extent, and severity of a deformity. The second is done to find signs of disease. The assessment of facial form includes evaluations of facial soft tissues and dentition. The goal is to diagnose a jaw deformity; however, as the skeleton is unexposed to inspection, one infers bone deformity by appraising the facial appearance and the dentition.

Humans have two jaws: upper and lower. The lower jaw is a single bone, the mandible. Yet the upper jaw is not a bone but a functional unit made by portions of four separate bones: the right and left maxillae and the right and left palatine bones, specifically the parts of these bones that are located below the zygomas. Clinically, the upper jaw is also called maxilla, a term that can be confusing because it is also the name of a bone (Fig. 37.3). Henceforth the term maxilla will be used to refer to the upper jaw.

During the physical examination, the examiner has to determine the size, position, orientation, shape, and symmetry of the jaws. The assessments of three of these properties, position, orientation, and symmetry, require a frame of reference. The most useful frame of reference is the one defined by the *standard anatomical planes*: median, coronal, and axial [2–4]. The median plane—the plane of symmetry of the face—divides the face into right and left halves, the coronal plane divides the face into anterior and posterior portions, and the axial plane divides the face into upper and lower parts. These planes are mutually perpendicular, i.e., orthogonal. The lines of intersection between the planes form the axes of the face. The intersection of the medial and axial planes forms the anteroposterior axis. The intersection of the medial and coronal planes forms the vertical axis, and the intersection of the axial and coronal planes forms the transverse axis. These axes define the cardinal directions of the face: front, back, cranial, caudal, right, and left (Fig. 37.4).

Throughout the physical examination, the planes of our reference system (median, axial, and coronal) are imaginary. We mentally construct them while observing the patient in a standard reference posture.

The standard reference posture of the head is the *natural head posture* (NHP) [4–6]. The NHP is a component of *standard international anatomical alignment*, a reference position in which a subject is standing erect, with feet together, hands on the side, and face looking forward toward the horizon. In this posture the head is not flexed nor extended, is not rotated, and is not tilted.

Clinical Assessment of Jaw Position

During the physical examination, one determines the position of the maxilla and mandible in three-dimensional space. This is done separately for each facial axis: anteroposterior, vertical, and transverse.

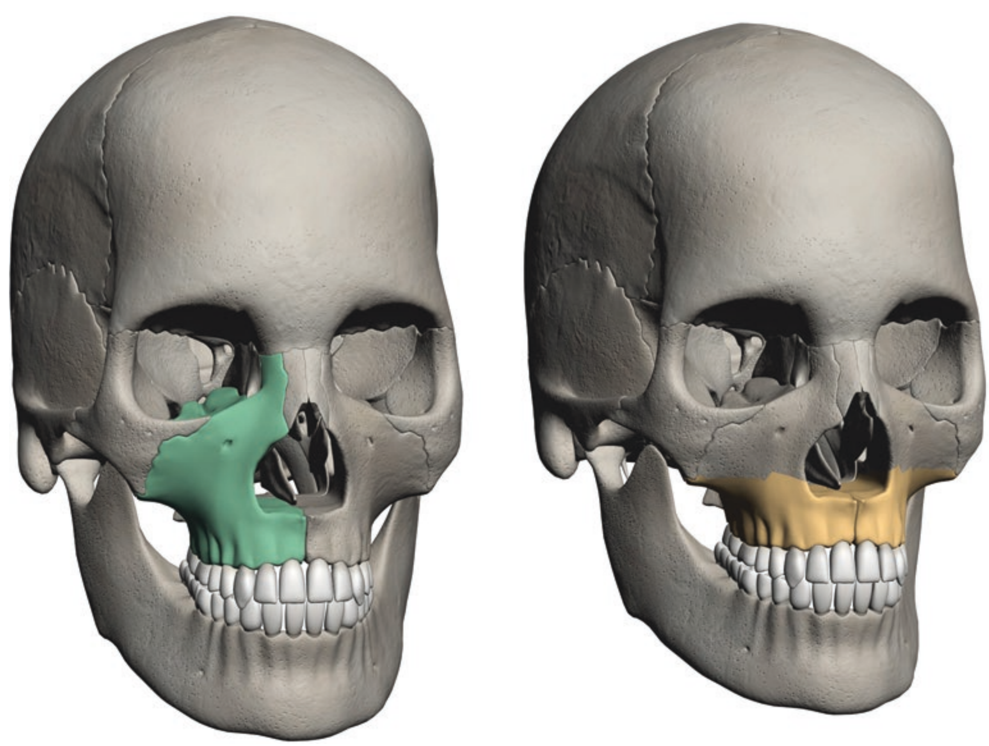

Fig. 37.3 Different definitions of the maxilla. On the left figure, the maxillary bone is depicted in green. On the right, the upper jaw—also called the maxilla—is depicted in yellow

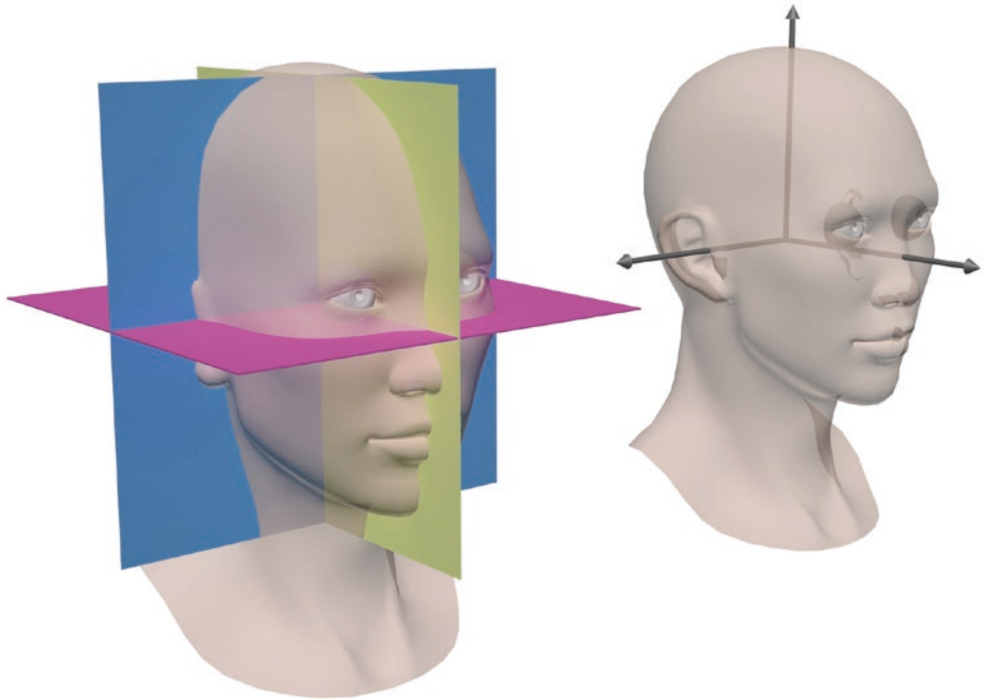

Fig. 37.4 Standard anatomical frame of reference. On the left, the median plane is depicted in yellow, the axial plane is depicted in red, and the coronal plane is depicted in blue. The lines of intersection between the planes create the axes on the coordinate system (right figure)

Anteroposterior

One infers the anteroposterior position of the jaws by evaluating the anteroposterior occlusal relationships and the facial profile. The occlusal relationships are appraised at three different sites: first molar, canine, and central incisor (Fig. 37.5). In this appraisal, the frame of reference is the upper dentition, i.e., the examiner gauges the anteroposterior position of the lower teeth in relation to hypothetical static upper.

Angle's molar relationship assesses the position of the buccal groove of the lower first molar in relation to the mesiobuccal cusp of the upper [7]. In an ideal Class I molar relationship, these landmarks coincide. In a Class II relationship, the lower molar groove is behind the upper cusp, and in a Class III, it is in front. A similar assessment is done in the canine region. In a Class I canine relationship, the lower-canine-first-premolar embrasure coincides with the cusp of the upper canine. In a Class II, the embrasure is behind the upper canine cusp, and in a Class III, it is in front.

Finally, in the incisal region, we measure the overjet. Overjet is the horizontal distance between the incisal edges of the upper and lower central incisors. When the lower incisal edge coincides with the upper, the overjet is zero. When it is behind, the measurement has a positive value. When it is in front, it will be negative. The ideal overjet is +2 mm.

Based on these assessments, one classifies the occlusion into neutroclusion, distoclusion, or mesiocclusion. In neutroclusion, the molar and canine relationships are Class I, and the overjet is normal. In distoclusion, the molar and canine relationships are Class II, and the overjet is either greater than normal (division 1) or normal (division 2). In mesiocclusion, the molar and canine relationships are Class III, and the overjet is smaller than normal, usually negative.

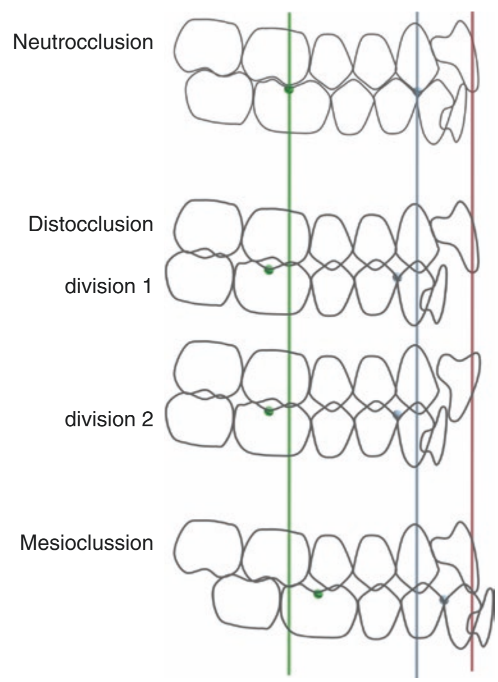

Fig. 37.5 Anteroposterior occlusal relationships

Distoclusion can occur in many different situations:

- Backward positioned mandible with a normal positioned maxilla

- Backward mandible with a forward maxilla
- Backward mandible with a less backward maxilla
- Normal mandible with forward maxilla
- Forward mandible with more forward maxilla

The opposite is true in mesiocclusion. Therefore, the finding of mesiocclusion or distoclusion reveals a discrepancy in jaw position between the upper and lower jaws and cannot be used on its own to determine anteroposterior jaw position. Moreover, the finding of neutroclusion does not necessarily imply normal anteroposterior jaw position, as both jaws can be retrognathic or prognathic.

To complete the assessment of anteroposterior jaw position, one also evaluates the facial profile [7–10]. Traditionally, clinicians have assessed the profile by classifying it into one of three categories: straight, convex, or concave. Yet this assessment lacks specificity. For example, a concave profile can occur when the upper jaw is normal and the lower jaw is prognathic, when the upper jaw is retrognathic and the lower jaw is normal, or when the upper jaw is retrognathic and the lower jaw is prognathic.

A better method is to compare the anteroposterior position of each jaw with the anterior boundary of the cranial base. Three structures related to the anterior cranial base have been used as reference: soft-tissue glabella, soft-tissue nasion, and the most anterior aspect of the cornea. They are used to define the anteroposterior position of a coronal plane of reference.

When assessing the facial profile, the patient should be in standard anatomical alignment (head in the NHP). While in this position, the clinician observes the patient from the side, imagining a coronal plane of reference, a plane that can be tangential to soft-tissue glabella, soft-tissue nasion, or the anterior surface of the cornea. At the same time, one infers the anteroposterior position of the jaws by assessing the position of the lips and chin in relation to this coronal plane (Fig. 37.6).

No perfect reference plane exists for determining the anteroposterior position of the jaws. Nasion can be obscured in Asian patients, as it is commonly located posterior to the cornea. Glabella can be distorted in frontal bossing. Distances from the cornea are difficult to gauge clinically. Despite these limitations, our clinical impressions are reliable, because our brains have an innate ability to discern the correct anteroposterior position.

Vertical

Clinically, one determines the vertical position of the maxilla by measuring the *rest-incisal-show* and the *smile-dento-gingival-show* (Fig. 37.7). Rest-incisal-show is the amount of upper incisor that is exposed when the lips are relaxed. It is the vertical distance from the upper lip *stomion* to the maxillary *incisal midpoint*. *Stomion* is the midpoint of the free edge of a lip—upper or lower. The *incisal midpoint* is

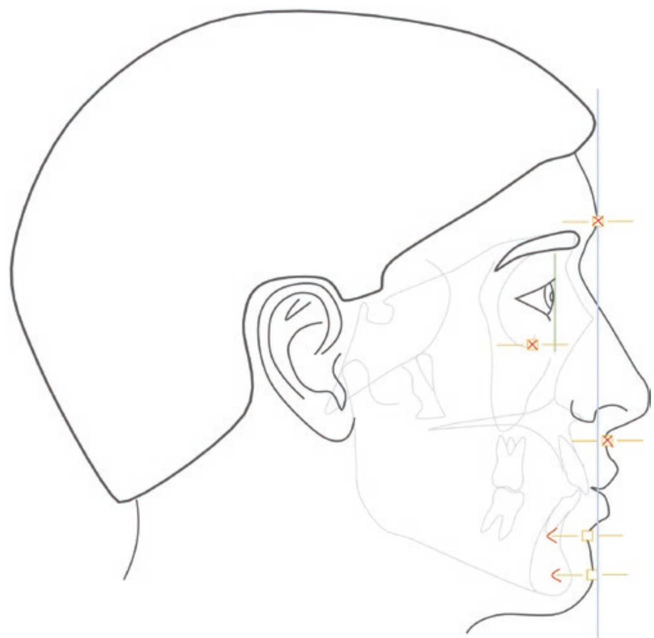

Fig. 37.6 Assessment of anteroposterior position (profile). The figure shows our markings for a patient with mandibular retrognathia

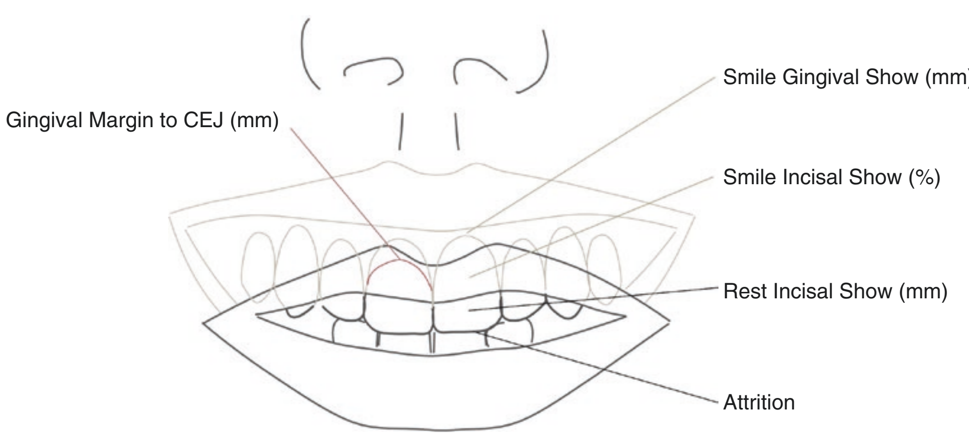

Fig. 37.7 Assessment of vertical maxillary position

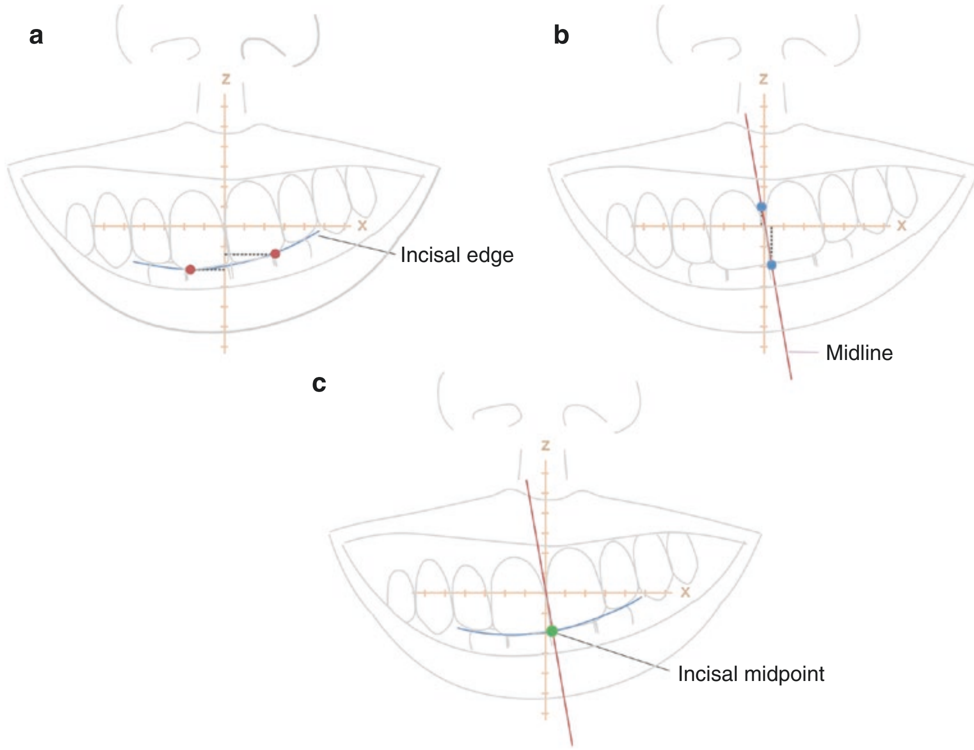

Fig. 37.8 Incisal midpoint. (**a**) The blue line is the dental arch. When the upper jaw is canted, each point (red dot) on the incisal arch has a different vertical position. (**b**) The red line shows the dental midline. When the upper jaw is canted, each midline point (blue dot) has a different horizontal position. (**c**) The incisal midpoint is located at the intersection of the dental arch (blue line) and the midline (red line)

the point at the intersection of the dental midline and the arc defined by the incisal edges (Fig. 37.8). It represents the middle of the dental arch. When the maxillary *incisal midpoint is* below stomion (baseline), the rest-incisal-show is positive; when it is above it, it is negative. Rest-incisal-show should be measured at the *incisal midpoint* rather than at other points on the incisal edges, because, when the maxilla is canted, incisal show varies at each location (Fig. 37.8).

Rest-incisal-show should be measured on an upright patient as it can increase when the patient is supine (Fig. 37.9). Additionally, the eyes of the examiner should be level with the patient's lips, as looking from above hides the teeth and looking from below exposes them. Negative incisal shows are difficult to measure. To overcome this problem, the authors place a piece of wax in the lingual surfaces of the upper incisors, extending it downward below the lip. Next, one asks the patient to relax his lips and marks (on the wax) the position of the upper lip stomion. Finally, one pulls the upper lip up with a caliper and measures the distance from the mark to incisal midpoint (Fig. 37.10). Some patients may have incisal attrition—wearing of the incisal edges because of grinding. In this situation, the examiner should add the amount of tissue loss to the measurement.

To determine the vertical position of the maxilla, the examiner compares the patient's *rest-incisal-show* with normal values. Gender, age, ethnicity, and the length of the upper lip influence these values [11]. Female patients have more incisal show than males. Incisal show also decreases with age [11, 12]. Caucasians tend to have more incisal show than patients of other ethnicities [11]. Patients with short upper lips tend to have more incisal show than those with longer lips [11]. For example, a five-millimeter incisal show is consider normal in a teenage girl with a short upper lip, although a half a millimeter incisal show is consider normal in a 60-year-old male. Patients with a negative incisal show are deemed to have *deficient maxillary downward displacement*. And patients with incisal shows above the normal range for their particular gender, age, ethnicity, and upper lip length are deemed to have *excessive maxillary downward displacement*.

As stated above, smile-dento-gingival-show is also used to determine the vertical position of the maxilla. Smile-dento-gingival-show is the amount of central incisor and labial gingiva that is displayed when smiling. Tooth show is measured as a percent of its height, whereas gingival show is measured in millimeters. Most patients with normal vertical maxillary position display 100% of the incisors [13] and up to 2 mm of gum during smiling. Patients with superiorly positioned maxillae show less than 100% of the incisors, while patients with inferiorly positioned maxillae display excessive amount of gum [14]. Yet the amount of tooth and gum that is displayed while smiling is not only related to the vertical position of the maxilla but also to lip animation and passive dental eruption.

Too much or too little tooth and gum display during smiling may result from abnormal lip animation [15, 16]. A hyperactive smile, the result of hyperactive smile muscles, produces a gummy smile; a hypoactive or weak smile, results in small tooth display. Hyperactive smile is diagnosed when

Fig. 37.9 Incisal show at rest. (**a**) Upright patient. (**b**) Supine patient

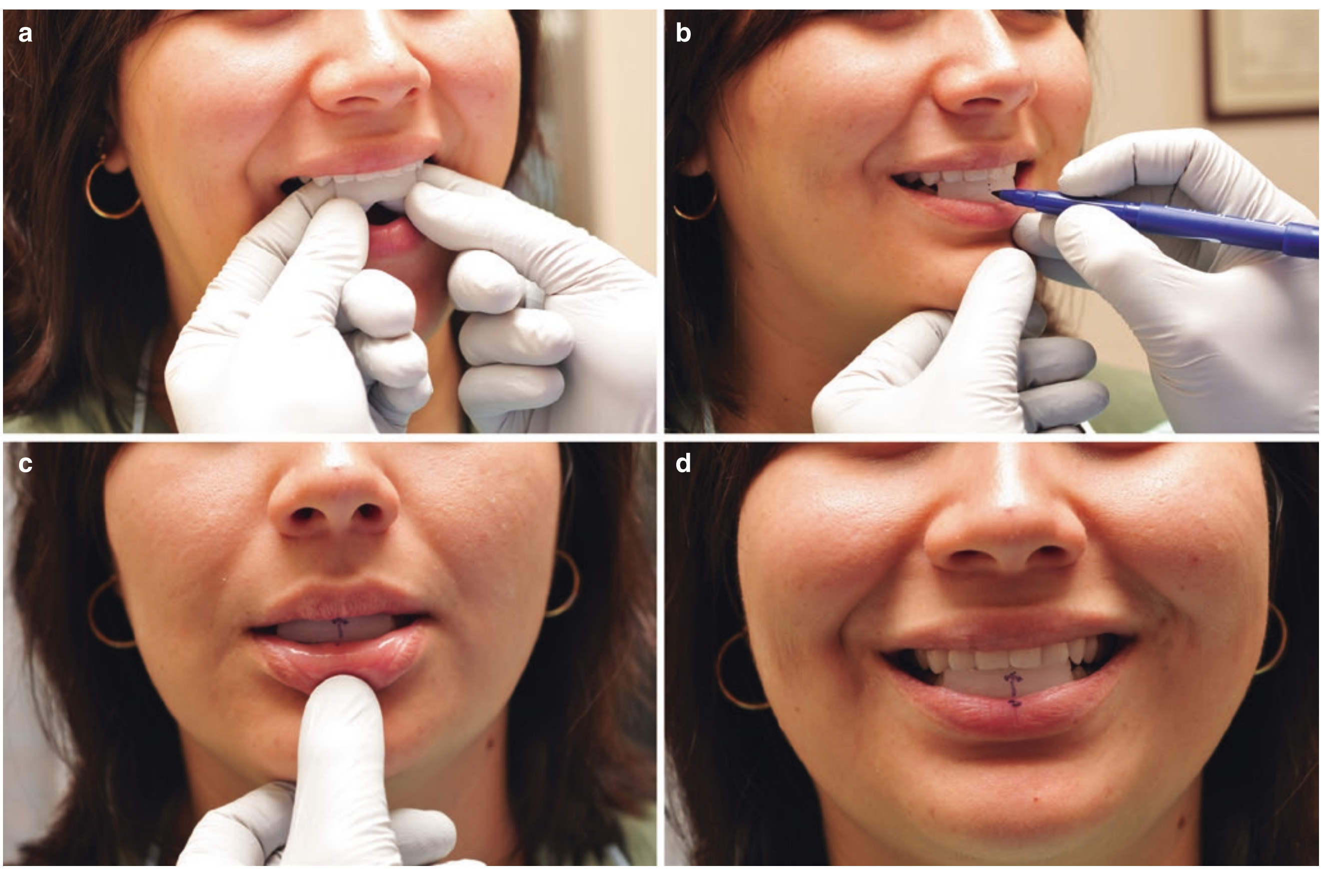

Fig. 37.10 Measuring negative incisal show. (**a**) Wax is placed behind the upper incisors. (**b**) The dental midline is extended into the wax. (**c**) The lips are placed in reposed, and the position of the upper lip stomion is marked of the wax. (**d**) The distance from the stomions to the upper incisal midpoint is measured

the gingival show is large, the rest-incisal-show is normal, and passive dental eruption (next paragraph) is normal. A hypoactive smile is diagnosed, when the smile tooth display is small and the rest-incisal-show is normal.

Tooth eruption consists of an active and passive phase. Active eruption is the movement of teeth toward the occlusal plane, whereas passive eruption is related to the exposure of teeth by apical migration to the gingiva. When passive eruption does not progress, the result is a dental crown that appears short because of the presence of excess gingiva covering the enamel. Clinically the most obvious sign of delayed passive eruption is a short clinical crown. Also, sulcus depths, from the gingival margin to the cement-enamel junction, are large (over 3 mm) [17]. Patients with delayed passive eruption may have large smile-gingival-shows despite normal vertical maxillary position. In this scenario, the smile-gingival-show is large, but the rest-incisal-show is small or normal.

Transverse

Clinically, transverse jaw position is established by measuring the distance between middle landmarks and the median plane. In the maxilla, one measures the position of a single point: the upper incisal midpoint. In the mandible, however, one measures the position of two points: the lower incisal midpoint and soft-tissue pogonion (the most prominent point of the soft-tissue chin). Transverse position should be measured at the incisal midpoint points rather than at any other point on the dental midline because when the jaws are canted, measurements vary with point position (Fig. 37.8). Also, when assessing the transverse position of the mandible, the mandible must be in centric relationship—the mandibular position in which the condyles are fully seated within the glenoid fossae.

Clinical Assessment of Jaw Orientation

During the physical examination, the pitch, roll, and yaw of the jaws are assessed in relation to the frame of reference of the whole face—the system defined by the median, axial, and coronal planes [3]. Pitch is difficult to measure clinically and is best assessed with radiographic cephalometry. Roll and yaw are related to symmetry and are discussed in the next section.

Clinical Assessment of Jaw Symmetry

The plane of symmetry of the face is the median plane. Midline landmarks like glabella, nasion, subnasale, incisal midpoint, and pogonion should lie on the median plane. Bilateral structures like the eyes, ears, and gonial angles should be aligned, on each side of the median plane, as mirror images.

During the physical examination, one infers the symmetry of the jaws by inspecting the face and by examining the dentition. To assess facial symmetry, the examiner must first stand in front of the patient, looking at the patient's face. While performing the examination one should mentally visualize the median plane and appraise two items: first, if midline structures are on the median plane and second, if bilateral structures are positioned as mirror images in relation to this plane. The examiner should also inspect the face from above and from below to determine if bilateral structures have the same anteroposterior position. All deviations should be measured and recorded (Fig. 37.11).

Clinicians also determine symmetric jaw alignment by examining the dentition. When the jaws are symmetrically aligned, the upper and lower incisal midpoints lay on the median facial plane. Also, corresponding right and left teeth have the same vertical position and the same horizontal distance to the median and coronal planes.

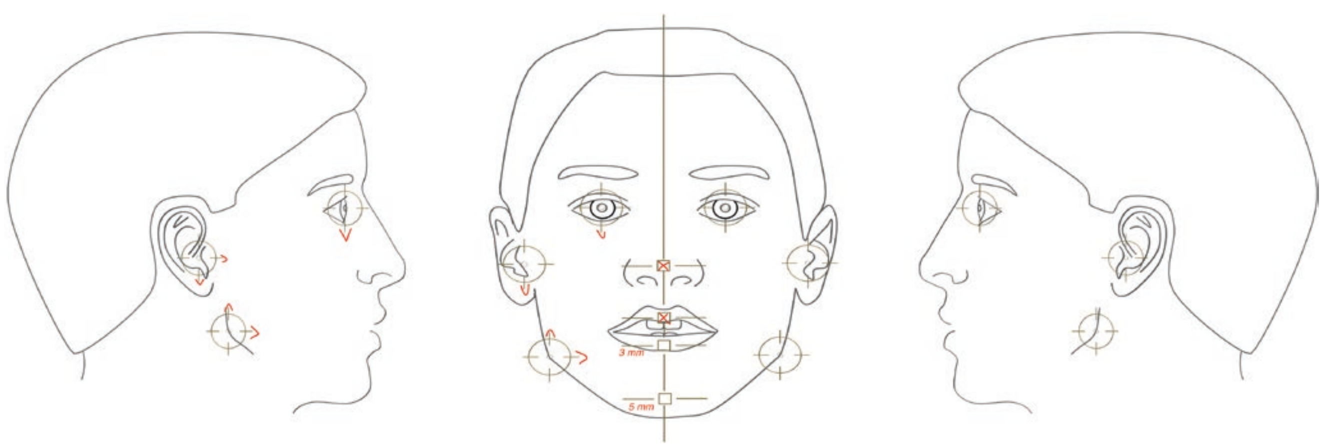

Fig. 37.11 Symmetry exam. The assessment of symmetry includes two items: (1) The transverse position of the jaws in relation to the median plane of the face. (2) The relative position of bilateral structures—also in relation to the median plane. In this figure we show our annotations for a patient with right craniofacial microsomia

Fig. 37.12 Clinically, maxillary roll (cant) can be quantified by measuring the vertical distances from the medial canthi to the upper teeth

Transverse deviations of the upper and lower incisal midpoints should be measured and recorded. The roll of the maxilla can be clinically determined by measuring, with a Boley gauge, the vertical distances from each medial canthus to the ipsilateral maxillary teeth (Fig. 37.12). Right-left differences that are consistent through the arch indicate canting (abnormal roll) of the upper jaw. These measurements should be interpreted with caution as they can be affected by local dental irregularities, vertical eye dystopia, and yaw malrotation of the upper jaw.

Diagnostic Test

The Jaw deformities cannot be fully assessed clinically. Hence there is a need to gather additional information from diagnostic tests. These tests include imaging studies, radiographic cephalometry, and dental model analyses.

Radiographic Cephalometry

The literal meaning of cephalometry is head measurement. These measurements can be taken clinically or radiographically. The term *radiographic cephalometry* is used to describe head measurements taken on an X-ray image. Traditionally, radiographic cephalometry has been performed on standardized two-dimensional X-ray images called cephalograms. In this chapter, however, the authors discus three-dimensional (3D) radiographic cephalometry, a relatively new method that aims to quantify facial form by using 3D data derived from computer tomography (CT).

Basic Principles of 3D Cephalometry

Cephalometry requires knowledge in three fields: biology, geometry, and statistics. In this section, the authors review the geometric principles of 3D cephalometry. Unfortunately, some of the geometry is challenging. Yet one should make an effort to learn it, as it is useful.

In orthognathic surgery, clinicians use cephalometry to determine the configuration of the jaws. Jaws like other objects have four basic geometric properties: size, position, orientation, and shape. In addition, they have a fifth property: reflection symmetry. In the following sections, the authors describe how to measure each one on these parameters in 3D.

Size Measurements

Size is an intrinsic property of an object that is independent of the space it occupies. One can measure size using linear measurements (e.g., length, width and height), areas, or volumes. In 3D cephalometry, the simplest size measurements are length, width, and height. These measurements are calculated as the distance between two points (landmarks) located in 3D space. For example, one can measure the width of the maxilla by calculating the distance between palatal cusps of the first molars.

Position Measurements

Position refers to *point* location in space. In 3D cephalometry, we are interested in determining the location of the jaws. Yet the jaws are complex three-dimensional objects made by thousands of points, each one with a different position. Therefore, to determine jaw location, one has to select one point to represent the whole jaw. Because there is no perfect point, in practice one has to use several. In the maxilla, clinicians use the anterior nasal spine (ANS), point A, and upper incisal midpoint. The anterior nasal spine represents the basal bone of the maxilla; point A represents the apical base, and the upper incisal midpoint represents the dentition. In the mandible, clinicians use pogonion, point B, and lower incisal midpoint. Pogonion represents the basal mandible, point B the apical base, and the lower incisal midpoint, the dentition.

Measuring position in one, two, and three dimensions requires one, two, and three numbers. Thus, any system that measures jaw position in 3D must utilize three numbers. In general, one can measure 3D position using one of the three systems: Cartesian, cylindrical, and spherical. Cartesian systems use three distances. Cylindrical systems use two distances and one angle. Spherical systems use one distance and two angles. Because spherical systems are not used in cephalometry, they will not be described here.

A 3D Cartesian coordinate system consists of three perpendicular axes (number lines) that cross each other at zero. The transverse axis is x, the anteroposterior axis is y, and the vertical axis is z. Each pair of axes forms a reference plane. In this system, one locates any point by measuring the distances from the point to each reference plane. Location is expressed using three coordinates (x, y, z).

Using a Cartesian system in 3D cephalometry is straightforward. The anteroposterior, vertical, and transverse positions of any landmark are expressed as (x, y, z) coordinates in a standard anatomical reference system. Relative position between two landmarks is easily calculated using arithmetic. For example, if the anteroposterior coordinate of point A is 62, and the anteroposterior coordinate of nasion is 60. Point A is said to be 2 mm in front of nasion ($62 - 60 = 2$).

A cylindrical system is an extension of the two-dimensional polar system. Thus, it is easier to learn a cylindrical system by first learning the polar system. A polar system resides on a plane. It consists of a fixed point—the *pole*—and a ray, the *polar axis*. From the pole, the polar axis points in a fixed direction. In this system, one determines the position of any point by first drawing a line segment from the point one is locating to the pole. This line segment is called the radius. Then, one measures the length of the radius (r) and the angle between the radius and the polar axis (θ). Position is expresses using two coordinates (r, θ) (Fig. 37.13).

A cylindrical system adds one axis to the polar system. This axis, called the *cylindrical axis*, is perpendicular to the plane of the polar system, passing through the pole. In a cylindrical system, one measures the location of any point in 3D space by first projecting the point on the plane of the polar system. On this plane, one then establishes the position of the point projection using the standard 2D polar coordinates (r, θ). The third coordinate is the distance from the point one is locating to the plane of the polar system.

Figure 37.14 shows an example that illustrates how cylindrical systems work. In this example, point B position is being measured in relation to sella nasion (the anterior cranial base). The origin of the coordinate system (the pole) is nasion. The polar axis is the ray that originates on nasion, pointing at sella. The cylindrical axis is perpendicular to the median plane, crossing nasion. One establishes the location of point B by first projecting this point on the median plane, then by measuring r and θ on the plane. The radius (r) is the distance from point-B-projection to nasion. Theta (θ) is the familiar SNB—the angle between the point-B-projection and sella nasion. The last coordinate (transverse position) is the positive or negative distance between point B and the median plane.

Orientation Measurements

Orientation is defined as the imaginary rotations necessary to move an object from a reference alignment to its current. Let us clarify with an example. Figure 37.15 shows an airplane taking off. Independent of its position or orientation in space,

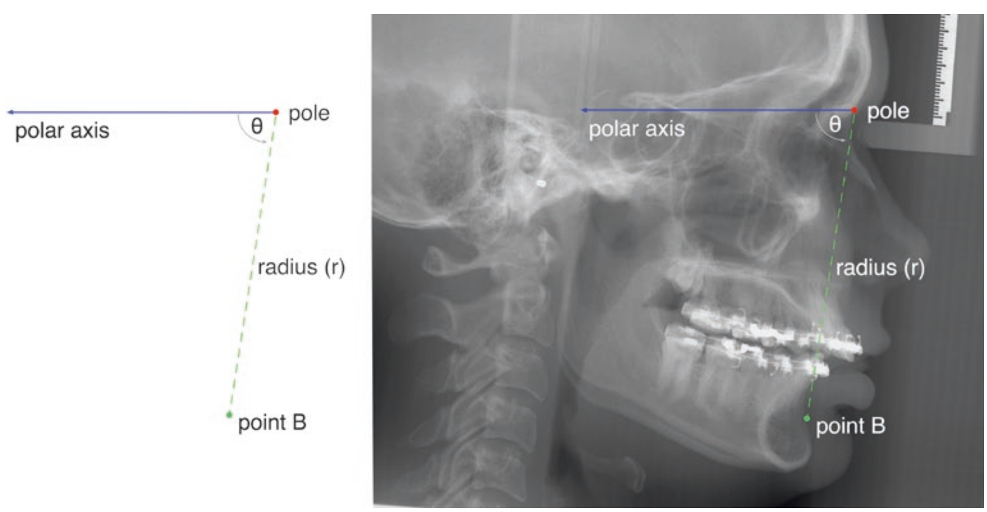

Fig. 37.13 Polar coordinate system

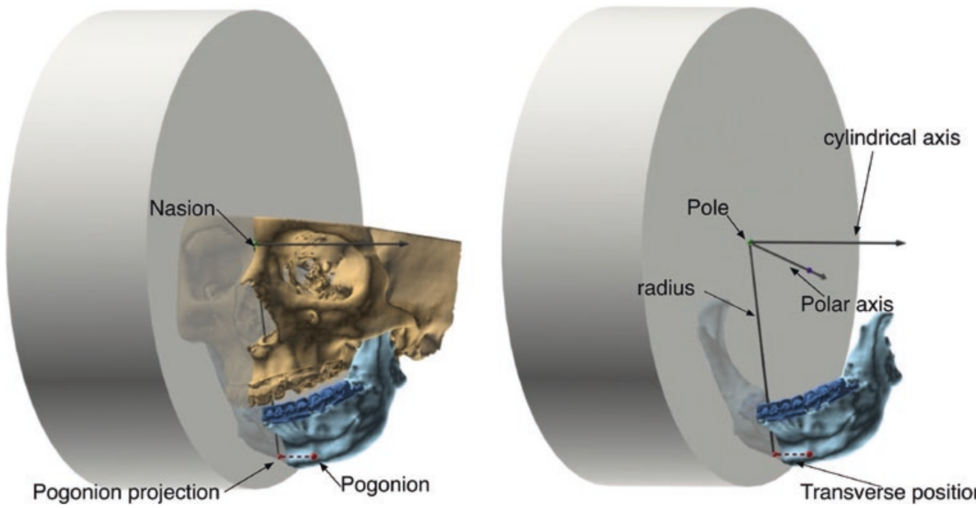

Fig. 37.14 Cylindrical system for 3D cephalometry. In this example we are measuring the position of pogonion in a patient with severe retrognathia and laterognathia. The median plane is the plane of reference of the system. The cylindrical axis is perpendicular to the median plane, passing through nasion. The angle between sella, nasion, and pogonion projection measures anteroposterior position. The length of the radius measures vertical position. The distance from pogonion to the median plane is transverse position

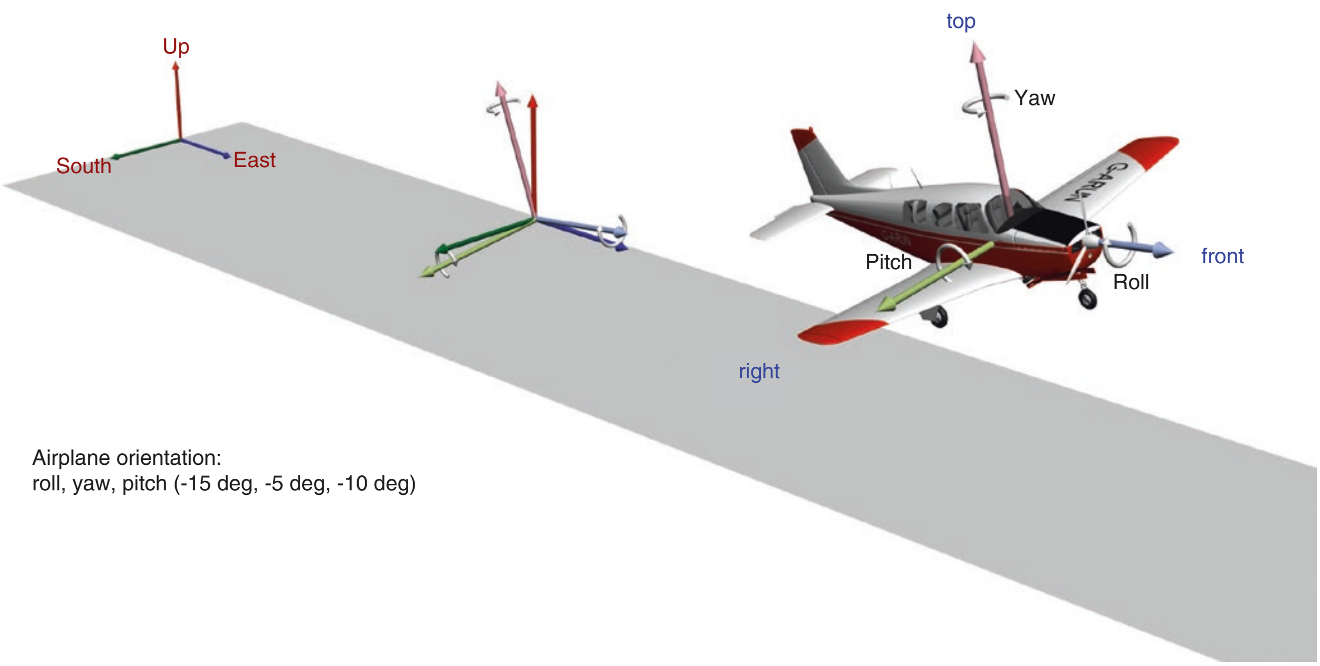

Fig. 37.15 Measuring orientation. On the left (beginning of the runway) is the world's coordinate system. Its axes point up, east, and south. On the right, the airplane is taking off. Centered in the airplane is the airplane's (object's) coordinate system (depicted in light colors). The red axis points to the top of the airplane, the blue axis points to the front of the airplane, and the green axis points to the right side of the airplane. In the middle of the runway, the authors superimpose the coordinate system of the plane on the coordinate system of the world

the airplane has a top, a bottom, a front, a back, a right side, and a left side. These intrinsic features can be used to draw three perpendicular axes: anteroposterior, top-bottom, and right-left (shown in the figure in light colors). Combined, they form the airplane's object coordinate system. Object coordinate systems belong to objects. They are determined by their configuration, and as such they translate and rotate with them.

The space around the airplane also has a frame of reference. Like the airplane's frame of reference, it also has three axes. In aeronautics, the axes of space are up-down, east-west, and north-south. Combined, they make the coordinate system of the world. Figure 37.15 shows the world coordinate system at the beginning of the runway in darker colors.

Measuring orientation, like measuring position is always relative. To measure it, one needs to decide on a reference orientation. For example, in this scenario, the airplane's orientation is being measured in relation to the world. To measure orientation, one superimposes the origin of object coordinate system (the airplane's) on the origin of the reference coordinate system (the world's). Once in this position, pitch, roll, and yaw are measured.

To measure jaw orientation, one compares the orientation of each jaw with the orientation of the whole head. For this, a computer program automatically constructs coordinate systems for each jaw (using a principal component analysis) and compares them with the coordinate system of the whole head (Fig. 37.16). The order in which the software measures pitch, roll, and yaw is essential. These angles are not commutative. This means that the order in which they are measured affects its values. The authors recommend measuring yaw, roll, and then pitch, as this order is clinically relevant.

Shape Measurements

Shape is the geometric property of an object that is not size, position, and orientation [1]. As one can see, shape is defined for what it is not, rather than for what it is. When comparing two objects, shape is the characteristic that remains after the objects have been scaled to the same size, have been placed on the same position, and have been rotated to the best possible alignment.

Figure 37.17 presents an example that illustrates this point. The figure shows two mandibles; the top one (orange) is the average mandible; the lower one (blue) is deformed. These mandibles differ in size, position, orientation, and shape. To appreciate the differences in shape, it is necessary to first scale both mandibles to the same size. Next, one has to place both mandibles in the same position. Finally, the deformed mandible is rotated until it is best aligned with the average mandible—target. This process is known as Procrustes superimposition [1].

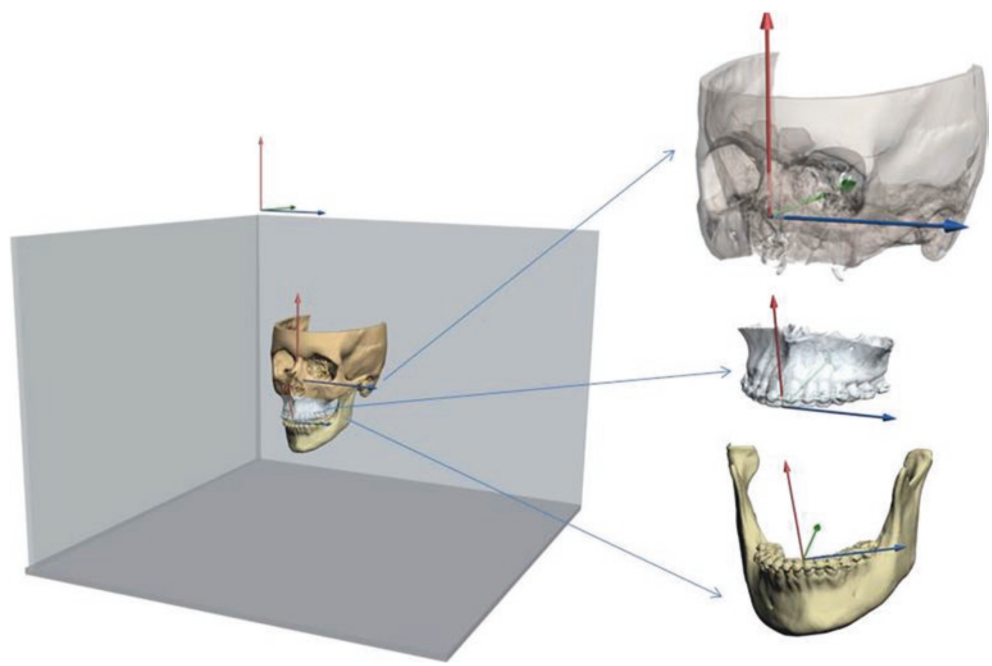

Fig. 37.16 Measuring orientation in 3D cephalometry. In 3D cephalometry, jaw orientation is established by comparing the orientation of the coordinate systems of each jaw with the frame of reference of the whole head

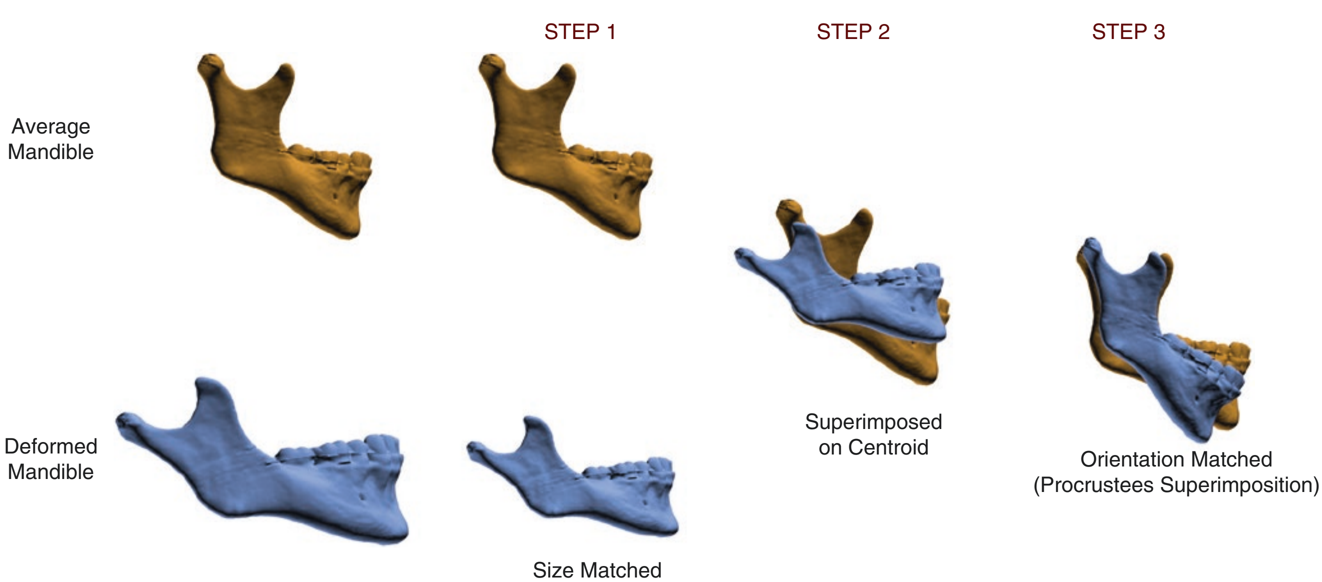

Fig. 37.17 Orientation Matched (Procrustes Superimposition)

As one can see in the example—after the differences in size, position, and orientation have been removed—the deformed mandible has a distorted shape. Specifically, it has an obtuse gonial angle and a relatively shorter ramus.

Symmetry Measurements

As mentioned before, there are two items related to symmetry. One is object symmetry and the other symmetric alignment. Object symmetry can be measured using different methods. Perhaps the most intuitive is Euclidean distance matrix analysis (EDMA) [18]. This analysis begins by selecting a group of midline and bilateral landmarks that delineate a jaw. Next one makes two sets of landmarks: right and left, the right set containing all right landmarks as well as all midline landmarks and the left set containing all left landmarks and the same midline landmarks.

Within each group, one then calculates the distances between all pairs of points. This creates two matrices (rectangular arrays of numbers): a matrix of right distances and matrix of left distances. Then, for each distance, one calculates the right to left differences. For example, if the distance from the right mandibular condyle to the right angle of the mandible is 40 mm, and the same distance on the left is 50 mm, the right-left distance difference is −10 mm.

Afterward, one normalizes the right to left differences. For example, the distance between the right condyle and the right angle of the mandible is 40 mm, and the same distance on the left is 50 mm. One first computes the mean condylar angle distance using the equation $\text{Mean distance} = \frac{(\text{Rigth distance} + \text{Left distance})}{2}$. Then, one uses this mean distance, 45 mm, as the basis of the normalization. To normalize the difference, one divides the right to left difference, −10 mm, by the mean distance, 45 mm. The resultant ratio, −0.2, is then converted to a percent, −20%. This number indicates that, on the right, the condylar angle distance is 20% smaller.

Finally, all the normalized right to left differences that radiate from a given landmark are averaged, the resultant number measuring the degree of intrinsic asymmetry of the given landmark (Fig. 37.18).

After measuring object symmetry, one measures symmetric alignment by calculating the movements (transformations) necessary to align the jaws to the median plane of the face. Three transformations are needed. They are transverse translation, roll, and yaw. Transverse translation places the incisal midpoint on the median plane. Roll rotates the jaws around the incisal midpoint until right and left landmarks are vertically aligned. Yaw rotates the jaws around the incisal midpoint, minimizing distance-differences between corresponding bilateral landmarks and the vertical reference planes—coronal and median. Ideal values for transverse position, yaw, and roll are zero.

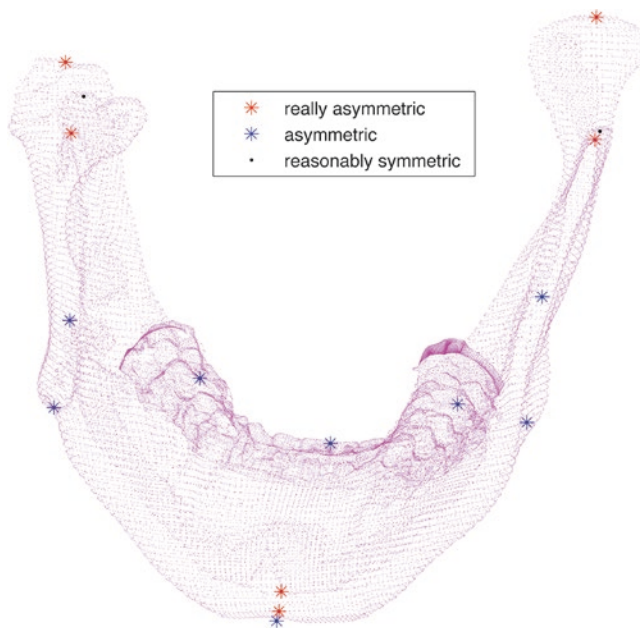

Fig. 37.18 Object symmetry analysis

Table 37.1 Gateno-Xia cephalometric analysis

			Maxilla	Mandible	
				Whole	Chin
Object symmetry					
Shape					
Size	Length				
	Width				
	Height				
Position	Anteroposterior				
	Vertical				
	Transverse	Symmetric alignment			
Orientation	Yaw				
	Roll				
	Pitch				

Gateno-Xia 3D Cephalometric Analysis

The authors' 3D cephalometric analysis is a grid (Table 37.1) [3]. In each row one assesses a different geometric property. Five properties are assessed: object symmetry, shape, size, position, orientation, and symmetric alignment. The columns belong to the individual facial units, e.g., maxilla and mandible.

In the first part of the analysis, *object symmetry*, one determines the intrinsic symmetry of each jaw. In the second part, *shape*, one measures the shape of the jaws using a 3D Procrustes analysis. In the third part, *size*, one measures the dimensions of each jaw: length, width, and height. In the fourth part of the analysis, *position*, one measures the location of the jaws on each facial axis—anteroposterior, vertical, and transverse. Depending on the preference of the clinician, position can be measured using a 3D Cartesian system or a cylindrical system. In the last part of the study, *orientation*, one measures the orientation of the jaws (yaw, roll, and pitch). *Symmetric alignment* is a composite of three measurements: transverse position, yaw, and roll.

Dental Model Analysis

A dental model analysis is an essential component in the evaluation of patients needing orthognathic surgery. It is done at least twice: before orthodontics and before surgery. The first analysis—the initial dental model analysis—guides orthodontic treatment; the second—the progress dental model analysis—establishes readiness for surgery.

In orthognathic surgery, surgeons and orthodontists collaborate to normalize the jawbones and the occlusion. In the first stage of treatment, an orthodontist aligns the upper and lower teeth to their corresponding jaw, creating normal dental arches. A surgeon then aligns the arches to each other during surgery. The orthodontist's task is complex. One has to coordinate the dental arches, so they can be placed in normal intercuspation at surgery. Coordination of dental arches entails giving the dental arches (upper and lower) corresponding forms. An initial dental model analysis shows the clinician how the pretreatment form deviates from the target, essential information one needs to plan correction.

An initial dental model analysis includes the following items:

- Analyses of shape:
  - Arch shape correspondence
  - Dental alignment
  - Dental leveling
  - Curve of Spee
  - Buccolingual inclinations
- Analyses of size:
  - Spacing
  - Arch width
  - Bolton assessment

A dental model analysis has many items. The authors classified them into two groups: appraisals of *shape* and appraisals of *size*. The first appraisal of shape is *arch shape correspondence*. For teeth to fit into a normal occlusion, the shapes of the upper and lower dental arches must be similar. This is called arch shape correspondence. To assess it, one looks at the occlusal surfaces of both models simultaneously, mentally comparing the shapes of both arches. Dissimilar shapes are a problem: a "U"-shaped lower arch will not fit a "V"-shaped upper arch, a square lower arch will not fit a "U"-shaped upper arch, etc.

The second appraisal of shape evaluates *dental alignment*. In perfect alignment, the incisal edges of the incisors and the buccal cusp ridges of canines, premolars, and molars make a catenary arch. Misalignment occurs when the teeth are not aligned in an arch, either because of malrotation or tipping.

The third shape appraisal evaluates *dental leveling*. Leveling refers to the vertical position of teeth in relation to the occlusal plane. The occlusal surfaces of all teeth should be on the plane.

The fourth shape appraisal assesses the *curve of Spee* [19]. The curve of Spee is the up-down curvature of occlusal plane. It starts in the canine and extends back to the last molar. An ideal curve of Spee is flat or has minimal upward concavity [20].

The fifth and last shape assessment appraises the *buccolingual inclination of posterior teeth*. In the mandible, the lingual cusps should be 1 mm lower than the buccal. In the maxilla, the buccal cusps should be 1 mm higher than palatal. Buccolingual inclination is assessed with a straightedge. In the mandible, the straightedge is placed on corresponding buccal cusps, and the gap between the tool and the lingual cusps is measured. In the maxilla, the straightedge is placed on the palatal cusps, and the gap between the instrument and the buccal cusps is measured.

The next group of items appraises size. Among them, there is *spacing*. *Spacing* is a comparison between the space available for the alignment of teeth and the space needed. In the first step, one calculates the available space, which is the arch perimeter from one first molar to the other. In the second step, a provider measures the space needed, which is the sum of the widths of individual teeth—premolars, canines, and incisors [7].

Another essential component of the size appraisal is *arch width*. It is measured at the first molars. In an ideal Class I occlusion, the mesiopalatal cusps of the upper first molar occlude with the distal fossae of the lower first molars. Thus, the distance between the mesiopalatal cusps of the maxillary first molars should be the same as the distance between the distal fossae of the mandibular first molars. A discrepancy between these measurements may reveal an underlying apical-base deformity.

The final item is the *Bolton assessment*. This analysis was designed following the observation that in order to obtain the proper interdigitation and arch coordination in a Class I relationship, the width of the lower teeth has to be proportional to the width of the upper teeth. Bolton discovered that a Class I canine occlusion is only possible when the upper and lower teeth have a specific proportion. The sum of the widths of the lower anterior teeth must be 77% of the sum of the widths of the upper anterior teeth [7]. Failure to account for a Bolton discrepancy commonly results in lack of arch coordination.

Treatment Planning

Orthognathic surgery treatment has three well-defined stages: presurgical orthodontics, surgery, and postsurgical orthodontics. In the first stage, an orthodontist aligns and levels the teeth, removes unwanted compensations, and coordinates the dental arches. In the second stage, surgery takes place. In the final stage, an orthodontist completes the orthodontic movements.

Treatment planning is a process used to determine the particulars of treatment. Formal treatment planning is required at two different times (Fig. 37.19): before orthodontic treatment, *initial treatment plan*, and before surgery, *surgical treatment plan*.

Initial Treatment Plan

The initial treatment plan is completed before orthodontic treatment begins. The main goal of initial planning is to develop an orthodontic plan. The orthodontist and surgeon should agree on a tentative surgical plan. This plan is important as it influences important orthodontic decisions; for example, dental extractions, removal of dental compensations, and the creation of interdental spaces for osteotomies.

Surgical Treatment Plan

Before surgery is planned, the surgeon must determine if the patient is ready for surgery. This entails confirming that the goals of presurgical orthodontics have been met and that the patient's health has been optimized to ensure the lowest possible surgical risk.

Surgeons obtain *progress dental models* to see if the goals of presurgical orthodontics have been met. They hand-articulate the models in Class I occlusion to confirm that good occlusion is achievable. Good occlusion can be achieved when:

- Dental compensations have been eliminated.
- The teeth are well aligned, forming a smooth arch.
- The shape and size of the upper and lower dental arches match.
- Adjacent marginal ridges are leveled.
- Interproximal spaces are closed (unless spacing is needed to compensate for a tooth size discrepancy).
- The curve of Spee is flat or minimal.
- The labiolingual inclination of posterior teeth is normal.
- The incisal overjet and overbite are normal.
- The tooth size discrepancies (Bolton) have been dealt with.
- Occlusal contacts are maximized.

If good intercuspation is observed, and the risks of surgery are acceptable, the patient is ready for surgery.

Occasionally, good intercuspation cannot be achieved because of the presence of an *apical-base* deformity. The *apical base* is the part of the jawbones located around the apices of teeth. It determines the position of the dental roots. Because dental roots should not be moved outside the bone, maximal intercuspation cannot be achieved when the apical bases are deformed. For example, when the maxillary apical base is narrow, the posterior teeth will end being in crossbite despite adequate presurgical orthodontics. In these cases, the maxilla has to be segmented—separated into two or more tooth-bearing bone segments—so it can be expanded.

If good intercuspation cannot be achieved because of an apical-base problem, the surgeon should segmentalize the dental models to find out if good occlusion is achievable. When dental models are cut into pieces, each piece is hand-articulated into occlusion, and the segments are then glued back together. If the surgeon confirms that this operation can be safely performed on the patient, the patient is deemed to be ready for surgery.

It is important to note that jaw segmentation should not, routinely, be used to compensate for poor orthodontics. In the absence of apical-base problems, poor Class I intercuspation indicates that presurgical orthodontics should continue. In particular cases, however, the goal of presurgical orthodontics is not maximal intercuspation. For example, in patients with deep-bite Class II malocclusion, with a deep curve of Spee and a short anterior mandibular height, it may be best not to level the curve Spee prior to surgery, because this may result in intrusion of the anterior teeth and additional vertical foreshortening of the anterior mandible. A better approach may be to go to surgery before the curve of Spee is leveled. At surgery, the occlusion is set to a normal incisal overbite, with occlusal contacts limited to the incisors and second molars. Postoperatively, an orthodontist levels the mandibular occlusal plane by erupting the premolars, limiting intrusion of the lower incisors.

Once the decision has been made to proceed with surgery, surgical planning begins. A surgeon plans an orthognathic oper-

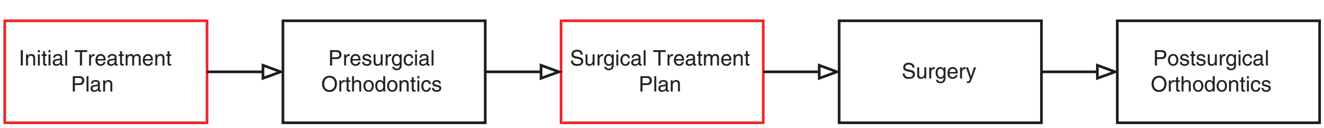

Fig. 37.19 Treatment planning. In orthognathic surgery formal treatment planning is done twice (red rectangles), at the beginning of treatment and before surgery

ation by simulating the surgical procedures and visualizing their outcomes. This process is iterated until the desired results are visualized. The name of this approach is Visualized Treatment Objective (VTO), a term that denotes that the plan is developed by visualizing the final outcome (i.e., the treatment objective).

The simulation of the operation is done on models that reproduce the craniofacial anatomy. Traditional planning methods utilized two-dimensional line drawings of plain cephalograms and stone dental models mounted on a dental articulator. These methods have significant limitations [2–4, 21–24] and are being phased out. This chapter presents a computer-aided surgical simulation (CASS) method [4, 25]. This method has three phases:

- Modeling
- Planning
- Preparing for plan execution

Modeling

In the modeling phase, one creates a 3D virtual model of the craniofacial complex. This model should:

- Have a mandible in centric relationship
- Accurately render the skeleton, the teeth, and the facial soft tissues
- Have a correct frame of reference

3D virtual models used for CASS should have a mandible in centric relationship. Centric relationship (CR) is the position in which the condyles are centered within the glenoid fossae. It is an important reference position in orthognathic surgery, as it is the only tooth-independent mandibular position that is reproducible [4, 26, 27]. Moreover, in this position, the condyles can rotate, for about 20° around an axis that passes near the center of both condyles [28, 29]. Rotation of the mandible around this hinge axis is called *autorotation*.

Having a virtual model in CR is necessary in single-jaw maxillary surgery and bimaxillary surgery, if the maxilla is cut first. In these operations, the mandible dictates the location of the maxilla. So any discrepancy in mandibular position between the virtual model and the patient results in postoperative outcomes that are different from planned. At surgery, the mandible will always be placed in CR; thus, the virtual model should have the same position. Occasionally, before surgery, it is impossible to place the patient in CR (e.g., patients with severe micrognathia). In these patients, the surgeon should consider doing mandibular surgery first as this obviates the need for accurate CR [26, 30].

Another important feature of the 3D virtual models is that they render the skeleton, the teeth, and the soft tissues well. Computerized tomography (CT) scans can be used to create 3D models of the craniofacial skeleton, teeth, and soft tissues. Yet the teeth of these models are not sufficiently accurate for surgical planning [22, 31–33]. The CASS protocol solves this problem by replacing the inaccurate teeth of the CT with accurate digital dental models [31]. Dental impressions or stone dental models are scanned to create these models. Scanning is done using an optical scanner, a micro-CT, or a cone beam CT. A model created by merging a CT with the digital dental models is called a *composite model* [25, 31].

The process of aligning digital dental models to the CT scan is called registration. It is done by aligning corresponding features that are present in both images. Different algorithms have been developed for this purpose. In these algorithms, the corresponding features can be points (i.e., landmarks) [31, 34], surfaces [35], or volumes [36]. They can be part of the structures being imaged or they can be fiducial markers—easy to identify parts that are placed in, on, or around the objects before image capture [37] (Fig. 37.20).

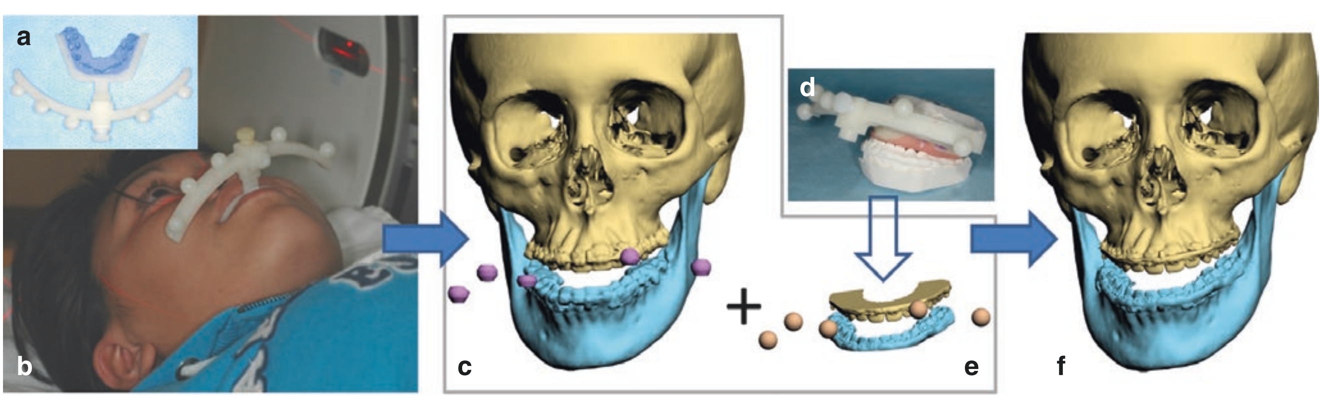

Fig. 37.20 Creation of a composite skull model. (**a**) Custom bite and facebow. The facebow has a set of fiducial markers (spheres). (**b**) Patient biting on the bite jig during image acquisition. The mandible is in centric relationship. (**c**) The midface, mandible, and fiducial markers are rendered as separate objects. Dental models are scanned in relation to the fiducial marker (**d**). Virtual dental models are created (**e**). (**f**) Composite model

Gateno et al. have developed and validated a fiducial registration system for making composite models [31]. In addition to allowing for accurate registration, it assures the mandible is in CR during scanning, a key feature [4, 26]. This system, presented in Fig. 37.20, uses a two-part device consisting of a bite jig and a fiducial facebow.

The bite jig has a dual purpose. It anchors the facebow to the patient and keeps the mandible in CR during image acquisition. It consists of a customizable stock frame with an anterior male coupler. To customize the jig, a clinician first adds a self-cured rigid bite-registration material to the frame and then places the jig between the teeth until the material is cured. During bite registration, the clinician seats the mandible into CR.

The plastic facebow attaches to the bite jig through a female coupler. It has a set of fiducial markers that is used for registration. Before CT scanning, the device—consisting of a bite jig and a facebow—is assembled and affixed to the patient. A CT scan is then taken while the patient is biting on the device. The resultant images portray the facial anatomy and the fiducial markers.

Afterward, the same device is placed between stone dental models (upper and lower). The models are then scanned. This creates a set of digital dental models surrounded by fiducial markers. In the last step, the digital dental models are registered in the CT, creating a composite model.

As mention above, 3D virtual model of the craniofacial skeleton should accurately render the facial soft tissues. Moreover, they should depict the relaxed position. This is accomplished by asking the patient not to animate his or her face during image capture and by avoiding deformations produced by posture or external sources. Some types of deformities produce postures that deform the soft tissues. Examples include curling of the lower lip by the upper incisor in Class II deep-bite malocclusions, pouting of the lips from over closure in vertical maxillary deficiency, and downward concavity of the upper vermillion in vertical maxillary excess and severe anterior open bite. The first two deformations can be avoided by opening the bite, but the last ones are unavoidable. As mentioned earlier, external sources can also deform the soft tissues. Items like chin rests, forehead holders, bite jigs, and dental trays are common culprits.

Virtual models used for planning must have an accurate *anatomic frame of reference*, for these frames are the bases of most decisions during planning. Incorrectly defined frames of reference can cause postoperative deformity. One can erect a frame of reference for a 3D model by using one of two approaches: anatomical landmarks or the NHP.

The first method uses anatomic landmarks to create a Cartesian frame. At first glance, the task seems trivial. The planner constructs the median plane using any three midline landmarks. He then makes the axial plane Frankfurt Horizontal and constructs Frankfurt using three of the four points that define it (right orbitale, left orbitale, right porion, and left porion). Finally, he builds the coronal plane, making it pass through both porions and keeping it perpendicular to the other two planes.

But this simple method only works when the face is perfectly symmetrical. In facial asymmetry, various combinations of three midline landmarks produce different median planes. For the same reason, various combinations of Frankfurt points result in different axial planes. Moreover, in facial asymmetry, Frankfurt Horizontal is usually not perpendicular to the median plane—a fundamental requirement of a Cartesian system. Finally, a coronal plane cannot be constructed if the two other planes (median and axial) are not perpendicular. Thus, as all faces have some degree of asymmetry, using landmarks to build a frame of reference is complicated.

An improvement is the *orthogonal best-fit method*, a method that takes into consideration the universal asymmetry of the face and the requirement of perpendicularity among the planes. A computer algorithm constructs three orthogonal planes, minimizing the distance between planes and key facial landmarks. The median plane is the best-fit plane for all midline landmarks, the axial plane is the best-fit plane for the Frankfurt landmarks, and the coronal plane is the best-fit plane for both porions. But as it is explained below, this method is also flawed.

An example can illustrate why the *orthogonal best-fit method* is unsatisfactory. Figure 37.21a shows the 3D CT scan of a hypothetical subject with perfect facial symmetry. In the ensuing year, she develops right condylar hyperplasia, resulting in left chin deviation. The rest of her face, including the maxilla, remains unchanged (Fig. 37.21b). After developing the asymmetry, she seeks treatment. A surgeon sees her and gets a 3D CT. He calculates the head's median plane using the orthogonal best-fit method (blue line depicted in Fig. 37.21c). This method would calculate the median plane as the plane that best fits all midline landmarks. But because some midline landmarks are deviated (the mandible's), the median plane will be skewed. Making assessments based on this skewed plane, he will incorrectly conclude that the maxilla is deviated to the right and that the chin is deviated to the left, when in reality only the chin is off, the maxilla is normal.

Why did this happen? This occurred because some of the landmarks used by the algorithm were affected by the asymmetry. In this case, the shifted mandibular landmarks skewed the median plane. Thus, one can conclude that facial asymmetries hinder the landmark method. Moreover, the results of this simple experiment made the authors reconsider the essence of the anatomical frame of reference, particularly when faced with asymmetry. After some reflection, they now understand that the anatomical frame of reference a clinician needs is the one a patient would have had if he or she did not have an asymmetry. They call it the primal frame of reference.

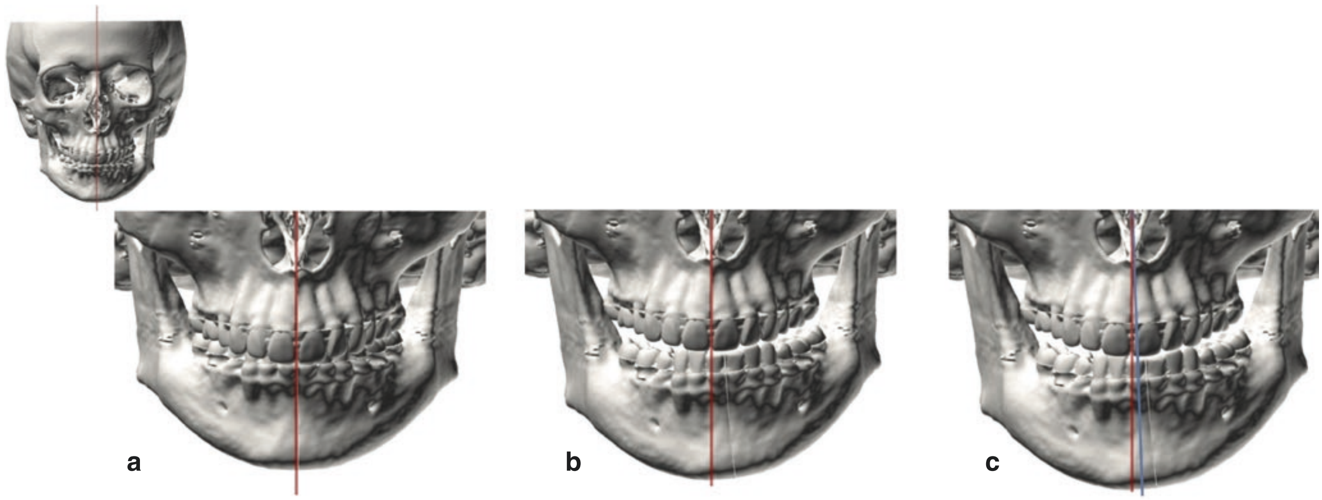

Fig. 37.21 Example that illustrates why using a best-fit method to create a facial frame of reference is inaccurate. (**a**) Hypothetical patient with facial symmetry (red line is the median plane). (**b**) Simulated unilateral (right) condylar hyperplasia. The chin and lower dental midlines are left deviated. (**c**) Best-fit method erroneously calculates the median plane (blue line)

In the hypothetical case presented above, the primal frame of reference can be easily calculated by excluding the skewed mandibular landmarks. Yet this case is simple as the rest of the facial skeleton is symmetric, but how does one calculate the frame of reference when all facial and cranial structures are grossly asymmetric? The second method that can be used to erect an anatomical frame of reference for the whole head—the natural head posture—can solve this problem.

The principle behind using the natural head posture (NHP) is that the primal frame of reference of the head can be derived from this posture. When humans stand erect, looking straight forward, the cardinal directions of their faces are orthogonal to gravity. The axial plane is perpendicular to the gravitational pull. The median and coronal planes are aligned with it. Thus, when the head is in the NHP, constructing a frame of reference for the face is simple. The axial plane is the horizontal plane that passes through both porions. The median plane is the vertical plane that best divides the face into right and left halves. The coronal plane is the vertical plane that is perpendicular to the other planes and is aligned with the coronal suture.

Since the NHP is unaltered by developing jaw asymmetries, the frames of reference calculated by this method are unaffected by these deformities. Unfortunately, this method is inconsistent because of two reasons. First, some patients have difficulty aligning their heads in the NHP. This is particularly true in children, patients with neuromuscular problems, patients with torticollis, and patients with eye muscle imbalances. Second, even within the same patient, there are temporal variations in the NHP. When one records the NHP on the same patient, at various times, one obtains different measurements. Most of the time, the measurements are close to each other, varying within 2°. Yet even these small variations are problematic. Figure 37.22 presents the example of a symmetric patient who rolled his head (around nasion) by 2° during NHP recording. This small error caused the upper incisal midpoint and pogonion to look right deviated—the upper incisal midpoint by 1.6 mm and pogonion by 2.6 mm—when they were not. These are significant errors.

There are two ways of orienting a CT scan to the NHP. One is to scan the head while in the NHP. The other is to scan the head in any orientation and then reorienting the resultant image to the NHP.

CT scanners are aligned with the world, an alignment that takes into consideration the orientation of the patient's body during scanning—supine or erect. If we place a patient in the NHP during CT acquisition, or its equivalent for a supine patient, the resultant image will automatically be in the NHP. Although this method seems simple, in practice, it is difficult to implement. In medical CT scanners, it is hard to set the head in the NHP when the patient is supine. In a cone beam CT scanner, where patients sit, chin rests and head holders commonly interfere with the NHP. Therefore, reorienting images into the NHP after CT acquisition ends up being more practical.

Three methods can be used to reorient a randomly oriented 3D CT to the NHP. One uses standardized photographs [4]; a second, laser levels [38]; and a third, orientation sensors [4–6]. In the first, standardized frontal and lateral facial photographs taken with the patient in the NHP serve as visual guides to manually reorient the 3D CT in the computer. This method is subjective; however, it is valuable for checking the outcome of advanced methods.

In the second method, a patient is first placed in the NHP. Then, the perpendicular lights of a laser level are shined

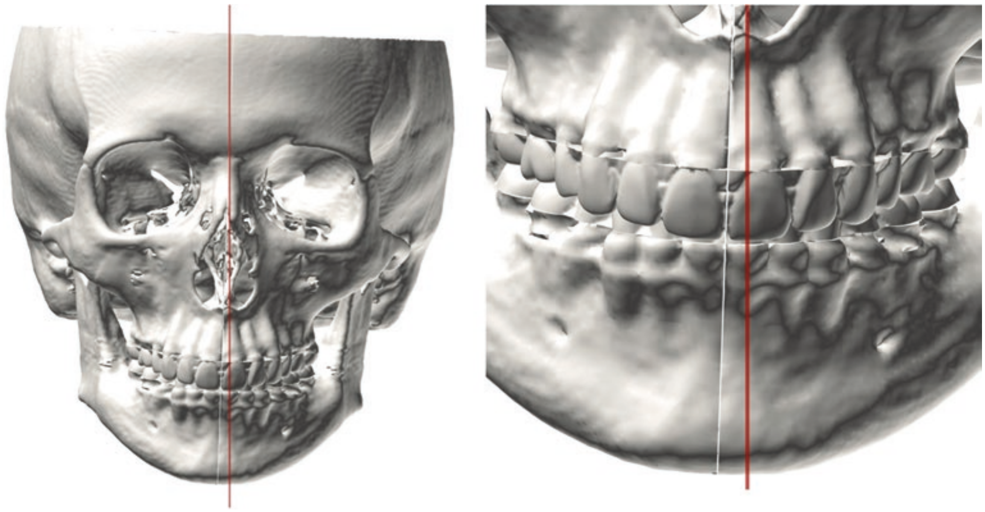

Fig. 37.22 Consequence of NHP recording error. This symmetric patient rotated his head 2° clockwise during NHP recording. It caused the upper and lower dental midlines to look deviated when they were not

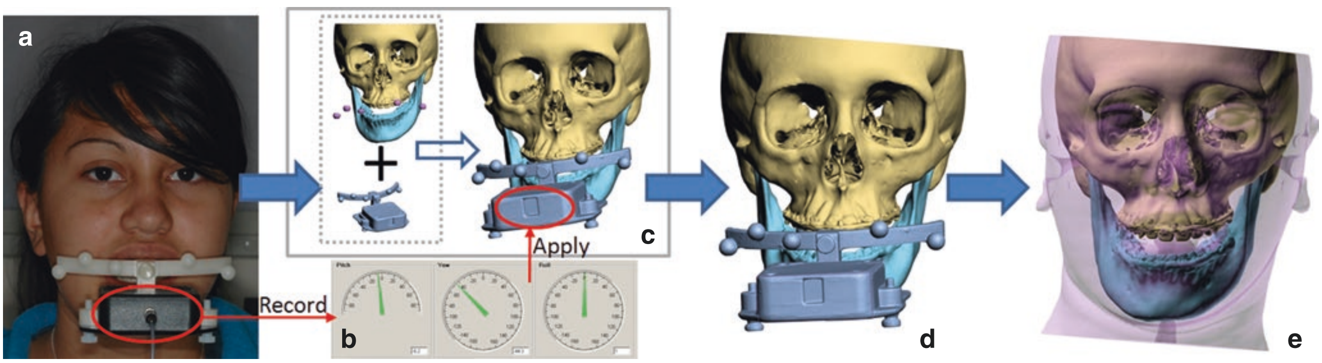

Fig. 37.23 Recording NHP with an electronic orientation sensor. (**a**) Digital gyroscope is attached to the bite jig and facebow, (**b**) The pitch, rool, and yaw of the gyroscope is recorded, (**c**) On a computer, the digital replica (computer-aided designed model) of the gyroscope is registered to the composite skull model (using fiducial markers) and the two objects are attached to each other. (**d**) The recorded pitch, roll, and yaw are applied to the center of the gyroscope replica, recording the composite skull model to NHP, (**e**) After the composite skull is oriented to NHP, the gyroscope replica is marked hidden. (From: Xia JJ, Gateno J, Teichgraber JF New Clinical Protocol to Evaluate Craniomaxillofacial Deformity and Plan Surgical Correction J Oral Maxillofac Surg 2009 pp. 2093–2016)

on the face of the patient, and the level is moved until the laser's vertical line is on the patient's median plane and the horizontal line crosses the external auditory canals. Next, a skin marker (a pen) is used to mark six points, on the skin of the face, establishing the orientation of the v lines directly on the patient. Following this, radiopaque markers are tapped on the skin marks, and the patient is CT scanned. After scanning, the makers are used to build an anatomical frame of reference. Unfortunately, this method has not been formally validated. A theoretical disadvantage is that it relies on skin landmarks that can be easily displaced.

The third method to reorient a CT to the NHP uses an orientation sensor to record the NHP before CT scanning (Fig. 37.23). The sensor is attached to the same bite jig used for registration. Next, the patient, with the bite jig between his teeth and the sensor in front of it, stands erect with his head in the NHP. In this posture, the pitch, roll, and yaw of the sensor are recorded.

Because the sensor is orthogonal to the bite-jig frame, the orientations of the sensor and the frame are always equal. Thus, establishing the orientation of the sensor while the patient is in the NHP establishes the orientation of the frame of the bite jig for the same posture. In the next step, the sensor is detached from the jig. Then a fiducial facebow is attached to the jig orthogonally, giving the bite-jig frame and the facebow the same orientation.

Next, the patient is CT scanned while holding the bite jig and facebow. Afterward, the CT, including the imaged facebow, is segmented and rendered as a 3D model. Finally, the 3D model is rotated until its facebow attains the measured NHP orientation, placing the whole 3D model in the NHP. The advantage of this method is that it has been validated in vitro and clinically.

In conclusion, both methods currently in use to erect frames of reference for the head—the anatomic landmark method and the NHP method—have significant limitations. With this in mind, the authors' laboratory is currently developing new methods to calculate the primal frame of reference for the face. Our goal is to eliminate the errors caused by current methods.

Planning

In CASS, surgery is planned using a VTO approach, meaning that surgery is simulated until the desired final outcome is attained. Surgical simulation is done on three-dimensional composite models, using specialized software. These programs can perform three basic functions: cutting and moving bones, articulating teeth, and morphing soft tissues.

Cutting and Moving Bones

Bone cutting is a computer operation that simulates an osteotomy. The cutting tool can be set as a simple plane or a three-dimensional array of adjacent planes. Both options are customizable in position, orientation, size, and thickness. To make a cut, an operator first sets the cutting tool into the planned osteotomy and then activates the cutting command. This operation separates an object into two new objects, objects one can recolor or renamed.

Moving bones involves two different types of transformations: translation and rotation. Translation is movement without rotation, i.e., sliding. Rotation is turning around a point. During planning, both types of transformations are needed. Translation can be made in the direction of the axes of the coordinate systems, whereas rotation can be made around any pivot point. In the software, the user can select the center of rotation.

Before translating or rotating objects in the computer, sometimes it is convenient to form groups of objects. In computer terms, this is known as object linkage [39, 40]. Linkage allows a transformation to be applied to the whole group rather than to a single object. An example occurs in single-jaw maxillary surgery. In this setting, the maxilla is first moved toward the mandible, placing it into final occlusion—usually maximal intercuspation. Next, the maxilla is linked to the mandible, so both can be rotated around the mandibular hinge axis without disrupting the final occlusion. Then the maxilla and mandible are rotated as a group until the maxillary central incisors are placed in an ideal vertical position.

Another example occurs in bimaxillary surgery. In this setting, the distal mandible is first moved toward the maxilla, placing it into final occlusion. Then, the mandible is linked to the maxilla, so the maxilla can be moved without disrupting the occlusion. Keeping the final occlusal relationship during all maxillary movements simplifies planning, as the distal mandible will automatically be in final position once the maxillary movements are completed.

Dental Articulation

In traditional planning, final occlusion is established by hand-articulating stone dental models. This maneuver is quick and reliable. When present, early contacts are easily noted, facilitating occlusal adjustments. Yet establishing final occlusion digitally is difficult. Upper and lower digital dental models are images that can overlap. Moreover, in CASS, there is no tactile sensation or real-time collision constraints. For these reasons, placing two dental models into occlusion becomes time-consuming. Furthermore, there are uncertainties as to the best alignment outcome. This is even harder when occlusal adjustments or dental arch segmentation is required. Although the authors' laboratory [35, 41, 42] and others [43–45] are working to solve this problem, our current clinical routine employs physical models as an intermediate step.

In the current CASS routine, final occlusion is first established on stone models. The models are then scanned in final occlusion creating a *digital final-occlusion template* (Fig. 37.24). This template is a computer object depicting upper and lower teeth in final occlusion. It has two parts, top (upper teeth) and bottom (lower teeth). Once the template is created, it is imported into the CASS software. In it, it is used to align the jaws of the composite model into final occlusion. The alignment is a simple

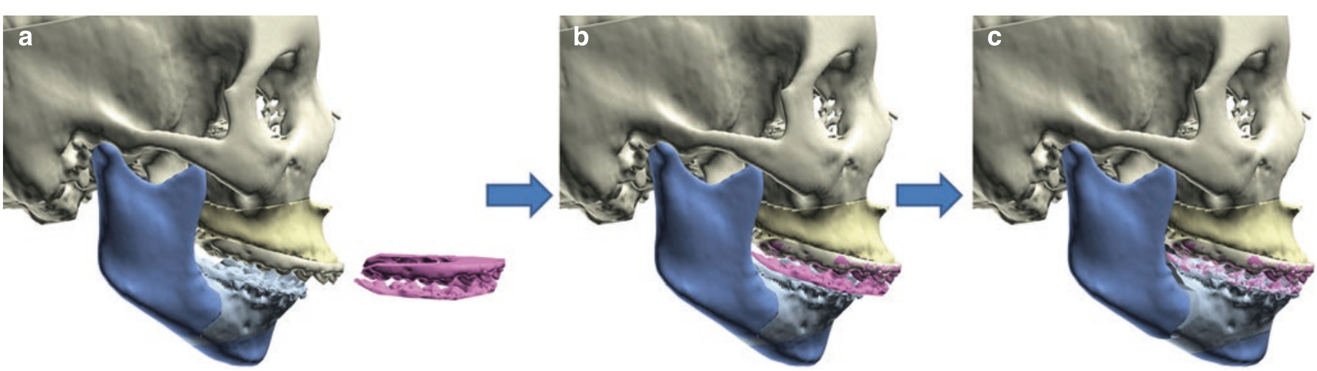

Fig. 37.24 Use of a final-occlusion template. (**a**) Patient with mandibular retrognathia needing single-jaw mandibular surgery. The digital final-occlusion template is depicted in pink. (**b**) The upper part of the final-occlusion template is aligned with the maxillary teeth. (**c**) The distal mandible is placed into final occlusion by aligning the lower teeth to the lower part of the template

two-step process. First, the template is aligned to one of the jaws. Then, the other jaw is aligned to the template. By aligning one part of the template to one jaw and then the opposing jaw to the template, this automatically places the jaws into final occlusion.

When the maxilla is the only jaw having surgery, the template is first aligned to the lower teeth, and then the upper jaw is aligned to the template. When the mandible is the only jaw having surgery or when they both do, the opposite sequence is done.

When the dental arches need segmentation, the use of a digital template to align teeth into final occlusion is more complicated. This scenario is best illustrated using an example: a patient needing a three-piece LeFort I osteotomy and a mandibular ramus osteotomy. As before, the occlusion is first established on stone dental models. In such a patient, the upper stone dental model is cut into three pieces, and each piece (i.e., segment) is independently moved and articulated into final occlusion. The intact lower arch is used as a guide. The independent movement of each segment changes the size and shape of the upper arch, creating a new intra-arch relationship among the upper jaw segment.

In the next step, one scans the stone dental models creating a digital final-occlusion template that not only captures final occlusion but also the new intra-arch relationship among the upper jaw segments. After importing a digital occlusal template into the CASS software, the template needs to be aligned to the upper teeth of the composite model (Fig. 37.25). But in the case of arch segmentation, the geometries are dissimilar. That is, the template shows the *new* upper arch alignment, whereas, the composite model shows the *original* condition. In this circumstance, the template is aligned to the upper jaw in two steps. First, the upper teeth of the template are *best aligned* to the teeth of the upper jaw. Then, the upper jaw of the composite model is segmented, and each LeFort I segment is aligned to the template—at its corresponding place. A similar approach is used when the lower arch is segmented.

Soft-Tissue Morphing

Current software packages are capable of simulating the soft tissue changes that occur with the movement of osseous or dento-osseous segments. These packages use different strategies to achieve this goal. The simulation methods must be accurate and fast. Yet attaining both is difficult, because these attributes are inversely related, the more accurate the model, the longer it takes to prepare and run. The facial soft-tissue envelope is a heterogeneous structure composed of different types of tissues: the skin, fat, connective tissue, muscle, and mucosa, each one with a different mechanical property [46]. Moreover, the properties are complex as they are nonlinear and anisotropic [46, 47].

Several models have been used to simulate soft-tissue deformations. They include *empirical-based models* [48–51], *mass spring models* [52–54], *finite element models* [49, 53, 55–60], and *mass tensor models* [61, 62]. *Empirical-based models* calculate soft-tissue deformation by using bone to soft-tissue change ratios, either from empirical knowledge [51] or from statistic calculations [48]. This method is fast [48, 51] but inaccurate [49, 61], as it does not consider the actual biomechanical tissue properties [48, 57, 61].

M*ass spring models* were initially developed for animation in the gaming industry, where rendering speed is more important than accuracy. In a *mass spring model*, the facial soft tissue volume is represented as a 3D array of vertices

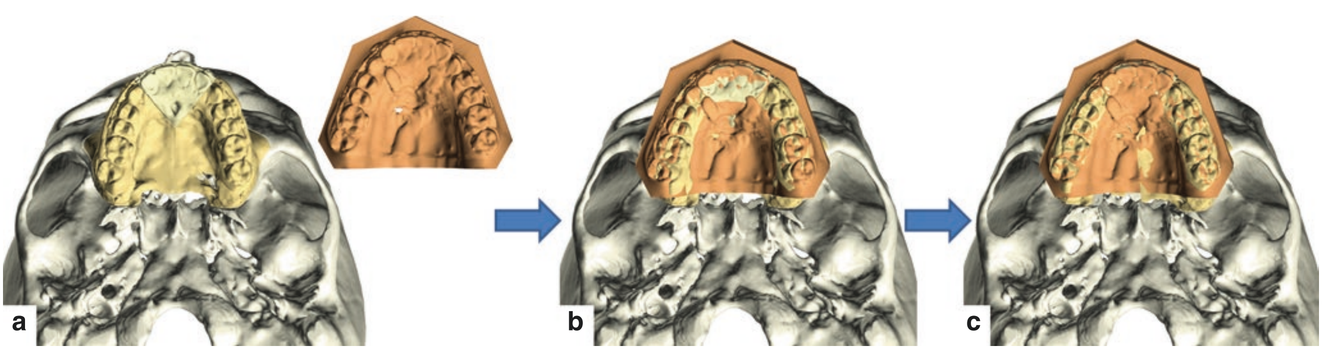

Fig. 37.25 Use of a final-occlusion template in a three-piece LeFort I osteotomy. (**a**) Three-piece LeFort I osteotomy. Initially, all segments (yellow) are in their original position. In orange, to the top and right of the skull model is the maxillary portion of the final-occlusion template. In this portion, the LeFort I segments are in final alignment. (**b**) The maxillary part of the final-occlusion template has been registered to the upper teeth, creating a best fit. Note that the posterior LeFort I segments (yellow) are medial. (**c**) The LeFort I dentoalveolar segments have been aligned to the template

(masses) attached by springs. This method is fast but lacks biomechanical relevance and clinical accuracy [48, 57, 61].

Finite element models divide the whole soft tissue volume into a large number of geometrically discrete volumes and assign material properties to them [61]. These models can vary from simple to complex. The simplest models assign a single homogeneous material property to the entire soft-tissue envelope. The complex ones fashion the envelope as a composite with different material properties. *Finite element models* are more accurate than *mass spring models*, as they have true biomechanical relevance. But the preparation and computation time of *finite element models* is significant.

Finally, *mass tensor models* can be considered a hybrid of *mass spring models* and *linear finite element models* that use a homogenous tissue property. They are reported to have fast computation times and acceptable accuracy [61].

Planning Algorithms

Orthognathic surgery is done to treat jaw deformities that can affect one or both jaws. Planning a single-jaw surgery is simpler than planning a double-jaw operation. The following sections present planning algorithms for single- and double-jaw surgery. It begins with the simplest scenario and ends with the most complex.

Single-Jaw Maxillary Surgery

In CASS, the simplest surgery to plan is a single-jaw maxillary surgery, an operation that is done when the maxilla is deformed and the mandible is normal (Fig. 37.26). In this scenario, the planner will make three decisions: final occlusion, vertical maxillary position (i.e., the position of the upper *dental midpoint)*, and the need for complementary genioplasty.

The planner begins the process by simulating a LeFort I osteotomy. When the dental arch needs segmentation, the maxilla is cut into two or more pieces. Next the maxilla is placed in final occlusion by articulating the whole maxilla or its segments on the mandible. Currently, this is being done with the help of a *digital occlusal template.* When the maxilla is cut into pieces, the pieces are grouped back together after they have been moved. This allows the maxilla to move as a single piece, henceforward.

Once final occlusion has been determined, the planner links the maxilla to the mandible. Linkage facilitates the next step, *autorotation*. In autorotation, the mandible is rotated around the condylar axis. Linking the maxilla to the mandible maintains final occlusion during the rotation.

Having already determined the ideal vertical position for the upper incisal midpoint (see evaluation section), the planner autorotates the mandible until the upper incisal midpoint reaches the desired vertical position. Next, one assesses the osteotomy site. Depending on the maxillary movement, the site may have gaps, butt joints, and regions of overlap.

During surgery, regions of overlap correspond to regions of bony collision. Thus, one should pay particular attention to these areas during planning. Planned ostectomies of regions of overlap can prevent collision. Yet large areas of overlap in or around the descending palatine artery, pterygoid plates, and the tuberosities are best avoided, as resecting large volumes of the bone in these areas is difficult. If the overlap is unacceptable, the planner should consider bimaxillary surgery.

In the final step of planning a single-jaw maxillary surgery, the planner reevaluates the chin. Reevaluation is needed because chin projection changes with autorotation. If the chin is normal, the plan is finished. If it is abnormal, the planner should simulate and plan a genioplasty.

Single-Jaw Mandibular Surgery

The second most complex plan is one for a single-jaw mandibular surgery, an operation that is done when the mandible is deformed and the maxilla is normal (Fig. 37.27). Assuming it involves osteotomies of the mandibular rami (sagittal, vertical, or inverted L osteotomies), one has to make four decisions: final occlusion, right proximal segment alignment, left proximal segment alignment, and final symmetry.

In the first step of planning, one simulates the osteotomies, usually in both rami. Sometimes, however, it also involves a body osteotomy—segmental dentoalveolar osteotomy, total dentoalveolar osteotomy, or a symphysial osteotomy. Bilateral ramus osteotomies divide the mandible into three pieces: a distal piece containing the dentition and two proximal pieces (right and left) having the condyles (Fig. 37.27).

In the next step of planning, the planner places the dentate segment(s) into final occlusion. Then, he aligns the proximal segments. Each proximal segment is rotated around the center of its condyle until the segment is well aligned with the distal mandible. Ideally, there should be no overlap between the segments, as overlap corresponds to areas of bony collision that can produce proximal segment misalignment at surgery. When overlap is noted, the surgeon should consider ostectomy of the area of overlap or a different osteotomy. Small regions of overlap are amenable to ostectomy; large regions require a different operation.

In the following step, the planner reexamines the chin. This is necessary because movement of the mandibular distal segment alters chin position. If the chin is normal, the planner proceeds to the final step. If it is abnormal, the planner should simulate a genioplasty, moving the chin segment until he is satisfied with the outcome.

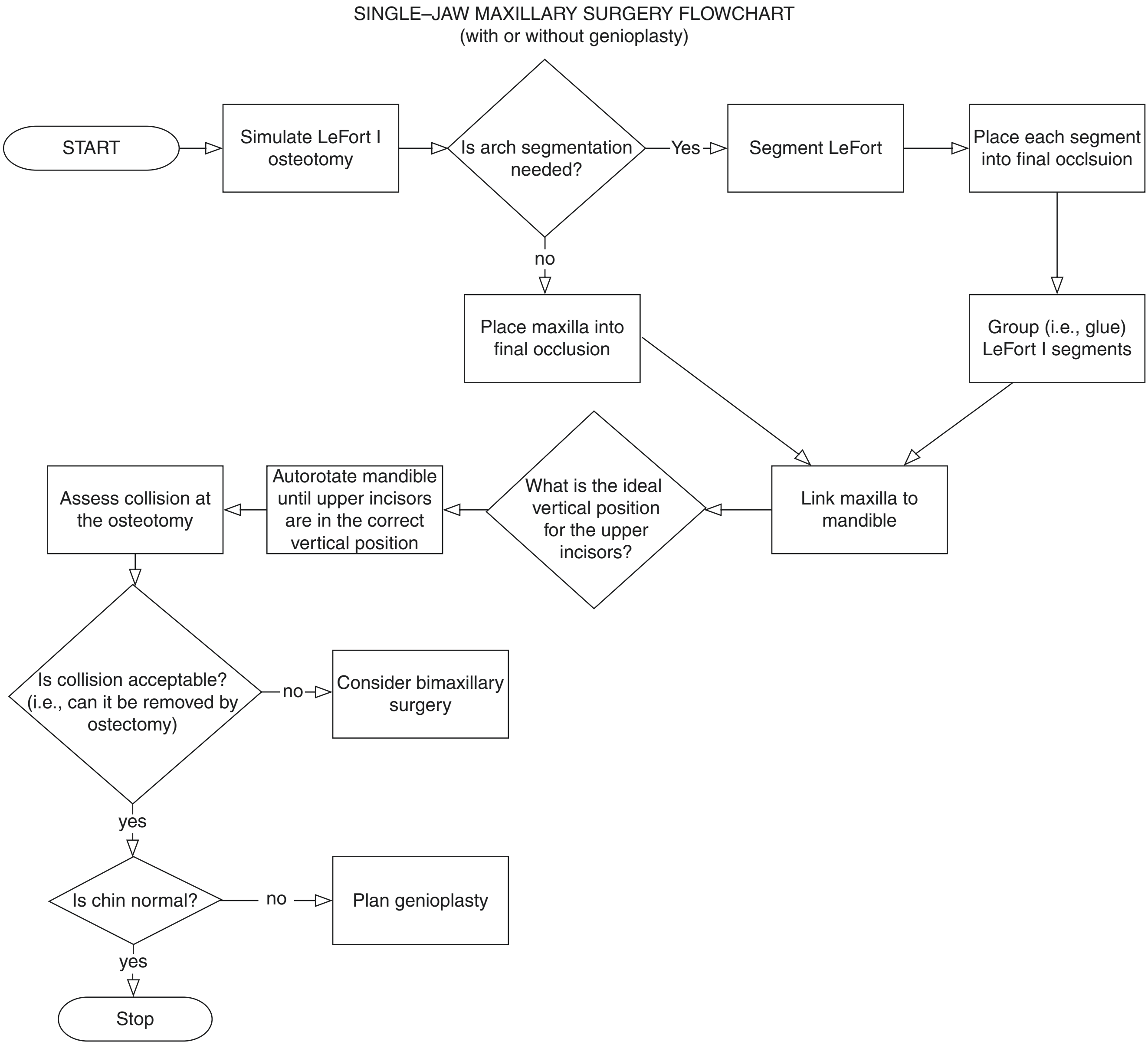

Fig. 37.26 Single-jaw maxillary surgery flowchart

In the last step, the planner assesses *final symmetry*. When the maxilla is normal and the mandible is abnormal but symmetric, placing the distal mandible in final occlusion maintains symmetry. But when patients have intrinsic mandibular asymmetry, placing the distal mandible into final occlusion does not correct the asymmetry. Since mild to moderate degrees of intrinsic asymmetry may be imperceptible to the eye, it is important to complete a final symmetry assessment on all patients. This is done using a *mirror image routine* (Fig. 37.28). In this routine, the composite model is cut in half across the median plane. One side is then copied and reflected (flipped) across the median plane, superimposing it over the contralateral half. Afterward, right-left differences are calculated using a Boolean subtraction—a mathematical method that shows differences between objects. If symmetry is good, the plan is complete. But if there is residual asymmetry, the surgeon should consider an osteoplasty. This may entail reduction or augmentation. Augmentation can be done with bone grafts or with alloplasts.

Double-Jaw Surgery

A double-jaw surgery is necessary when both jaws are deformed or when the discrepancy between the jaws is so large that both jaws should be moved, even when one of

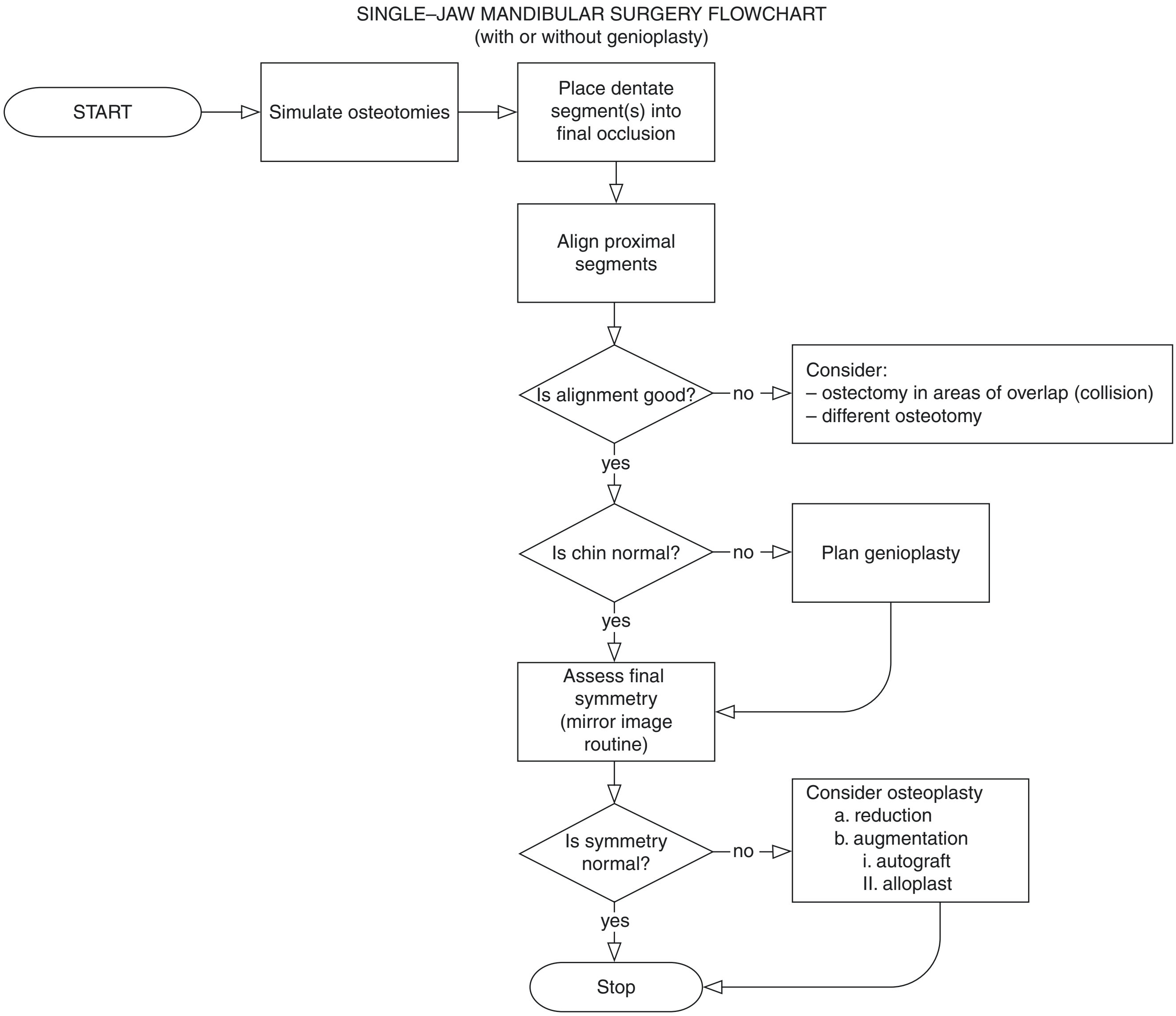

Fig. 37.27 Single jaw mandibular surgery flow chart

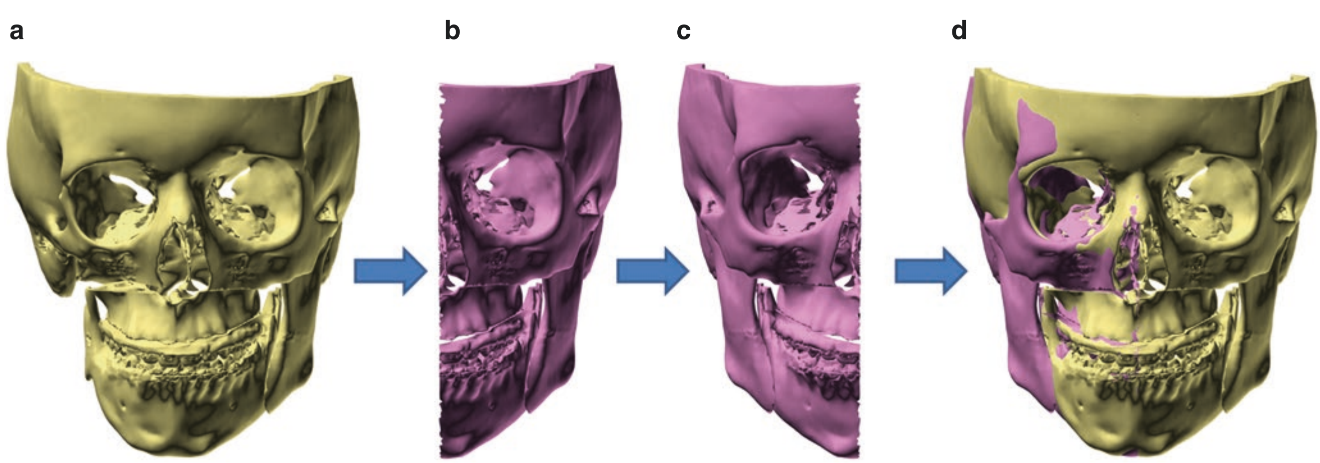

Fig. 37.28 Mirror imaging. (**a**) In mirror imaging, one side of the face is first copied (**b**). Next, the copy is flipped (**c**). Then flipped copy is superimposed on the contralateral side (**d**). Finally, side-to-side differences are calculated

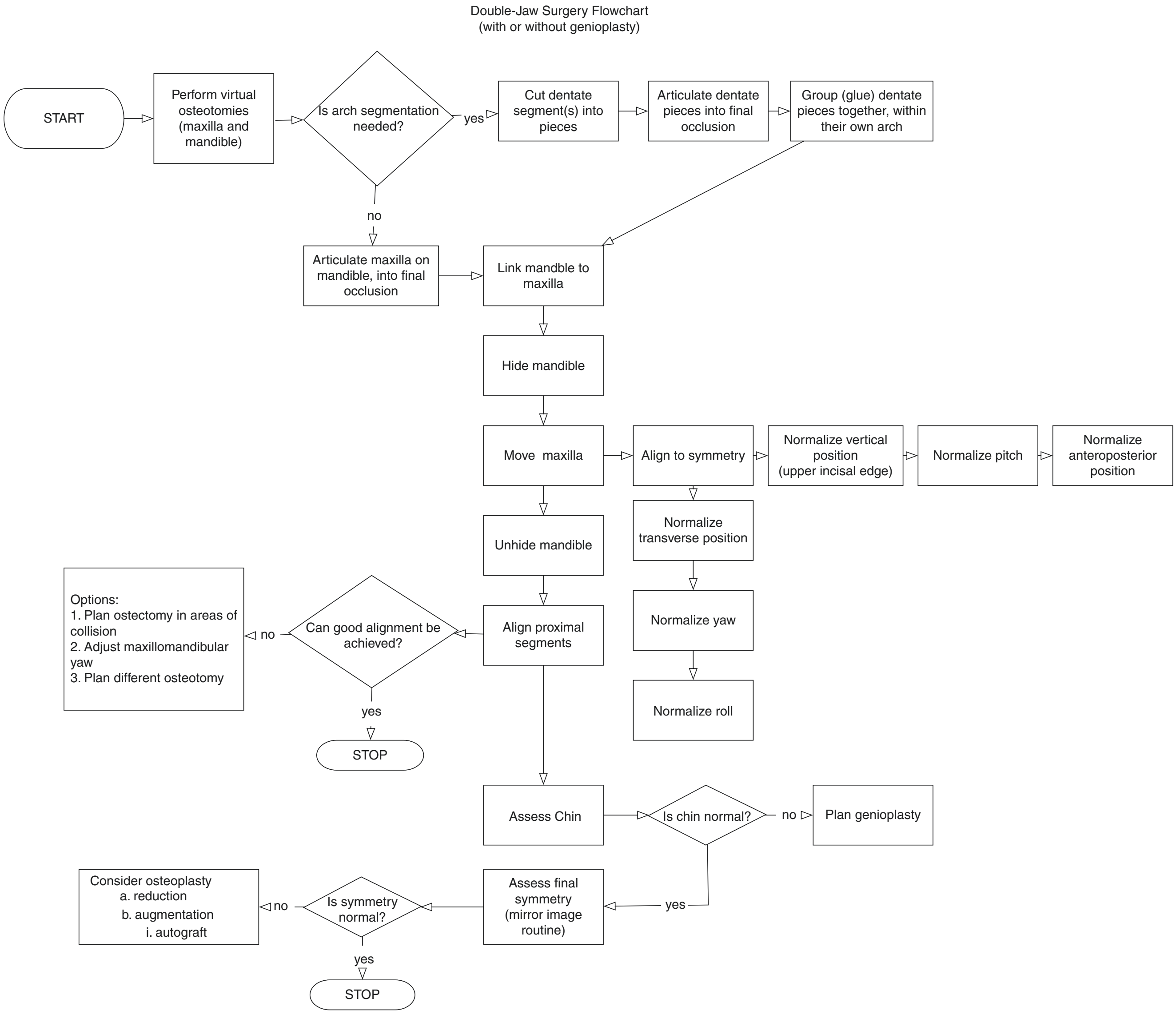

Fig. 37.29 Double-jaw surgery flowchart

them is normal. Planning a double-jaw operation is a complex multistep process. Planning without having a strategy costs time, produces errors, and results in unsatisfactory outcomes. Empirically, the authors have developed a planning algorithm to guide surgeons through this process. Although it has not been formally tested, it has been found most useful (Fig. 37.29).

Planning starts by simulating osteotomies in the maxilla and mandible. In the maxilla, one makes a LeFort I osteotomy. In the mandible, one usually makes bilateral ramus osteotomies but occasionally also body osteotomies. If dental arch segmentation is unnecessary, one proceeds with the next step: articulating the maxilla atop the mandible into final occlusion. If arch segmentation is needed, the planner first cuts the jaws into pieces and then articulates each piece into final occlusion. Presently, aligning the jaws into final occlusion is being done with the help of a digital final-occlusion template.

When the jaws are segmented, one needs to regroup the segments after they have been moved. Regrouping is the digital equivalent of gluing segments during physical model surgery. It allows the reestablishment of the maxilla or distal mandible as a single piece, facilitating future movements.

The next step is to link the distal mandible to the maxilla. This ensures that the distal mandible moves together with the maxilla. If the distal mandible is unlinked, the maxilla will move without the mandible, resulting in a change in occlusion. As the jaws are already in final occlusion, it is important to move them together.

Next, the mandible is hidden and the maxilla is moved into ideal alignment. A series of transformations (translations and rotations) are needed to reach this alignment, transformations that are best done on or around a single point, following a specific sequence. Empirically, the authors have determined that the best point at which all transformations should be performed is the *incisal midpoint*. This avoids iterations. For the same reason, they established the following planning sequence:

- Symmetric alignment
  - Normalization of transverse position
  - Normalization of yaw
  - Normalization of roll
- Normalization of vertical position
- Normalization of pitch
- Normalization of anteroposterior position

In the first step, the maxilla is symmetrically aligned to the median plane. This involves three transformations: transverse translation, yaw rotation, and roll rotation. Transverse translation places the maxillary *incisal midpoint* on the median plane. Yaw rotation pivots the maxilla around the incisal midpoint, making the posterior teeth are as equidistant as possible to the median and coronal planes. Finally, roll rotation pivots the maxilla around the incisal midpoint until right and left teeth are vertically aligned.

In the second step, the vertical position of the maxilla is normalized. The planner translates the maxilla up or down, placing its incisal midpoint on an ideal position—in relation to the upper lip stomion.

In the third step, one normalizes the maxillary pitch. The planner pivots the maxilla around the incisal midpoint until its pitch is optimized. Maxillary pitch rotation affects the following items:

- Inclination of the maxillary central incisors
- Inclination of the maxillary occlusal plane
- Airway size
- Projection of the anterior nasal spine (ANS)
- Chin projection

When deciding the ideal maxillary pitch for a given patient, one should take into consideration all of these items. The first three items relate to function, the last two to esthetics. Frequently, the planner needs to make compromises among these items based on the priorities of an individual case.

The inclinations of the maxillary central incisors and the occlusal plane are important for distoclusion—the separation of upper and lower teeth during eccentric movement of the mandible. The average inclination of the maxillary central incisors—to the horizontal plane—is 117.0° ± 6.9° for a male and 110.5° ± 9.1° for a female [63]. The average occlusal plane inclination—to the horizontal plane—is 9.3° ± 3.8° [64]. These values are useful when deciding the maxillary pitch.

Regarding the airway, decreasing maxillary pitch increases mandibular projection. When the mandible moves forward, the tongue moves with it, enlarging the retroglossal airway space. The opposite occurs when the maxillary pitch is increased.

Concerning the projection of anterior nasal spine (ANS) and the chin, increasing maxillary pitch (by rotating the maxilla around the incisal midpoint) increases the projection of ANS and decreases the projection of the chin. Increasing ANS projection rotates the nasal tip upward, widening the nasolabial angle. Decreasing maxillary pitch has the opposite effect.

The final adjustment needed to align the maxilla is anteroposterior position. The authors leave this adjustment for last because previous transformations can alter one's decision as to how much to advance the maxilla. For example, decreasing maxillary pitch or changing its yaw can produce collisions between the maxillary tuberosities and the pterygoid plates, collisions that can be easily avoided by advancing the upper jaw.

After the maxilla is set into an ideal alignment, the mandible is rendered. The distal segment of the mandible will automatically be in final alignment because it had been previously linked to the maxilla into final occlusion. Each of the transformations that were applied to the maxilla was transferred to the distal mandible.

In the following step, the proximal segments of the mandible are aligned. Each proximal segment is rotated around the center of its condyle until the segment is well aligned with the distal mandible. Ideally, there should be no overlap between the proximal and distal segments—as overlap corresponds to areas of bony collision. When present, segment overlap can be avoided by:

- Readjusting the yaw of the maxilla and distal mandible
- Planning resection (ostectomy) of the areas of overlap
- Planning a different ramus osteotomy

Readjusting the yaw of the maxilla and distal mandible by 1 or 2° can avoid proximal segment collision, without altering esthetics. Yet adjustments larger than 2° should be avoided as they can produce buccal corridor asymmetry—the right to left difference in the amount of posterior teeth displayed during smiling. To prevent displacement of previous corrections, all yaw readjustment must be made around the upper incisal midpoint.

Small areas of bony overlap are amenable to ostectomy. But large areas of collision that remain after maxillary yaw adjustment can only be avoided by selecting a different operation (e.g., by selecting an inverted L osteotomy over a sagittal split).

The final two steps, *chin assessment* and the *assessment of final symmetry*, are the same as those done for single-jaw mandibular surgery. Figure 37.30 shows a clinical example of a patient whose bimaxillary orthognathic surgery was planned with CASS.

Preparing for Plan Execution

Planning has no value if the plan cannot be realized at surgery. The ultimate goal is to have a surgical outcome that is identical to the planned outcome. In orthognathic surgery, this is attained when the surgeon accurately moves the bone segments to their planned location. Various procedures and appliances have been developed for this purpose. They

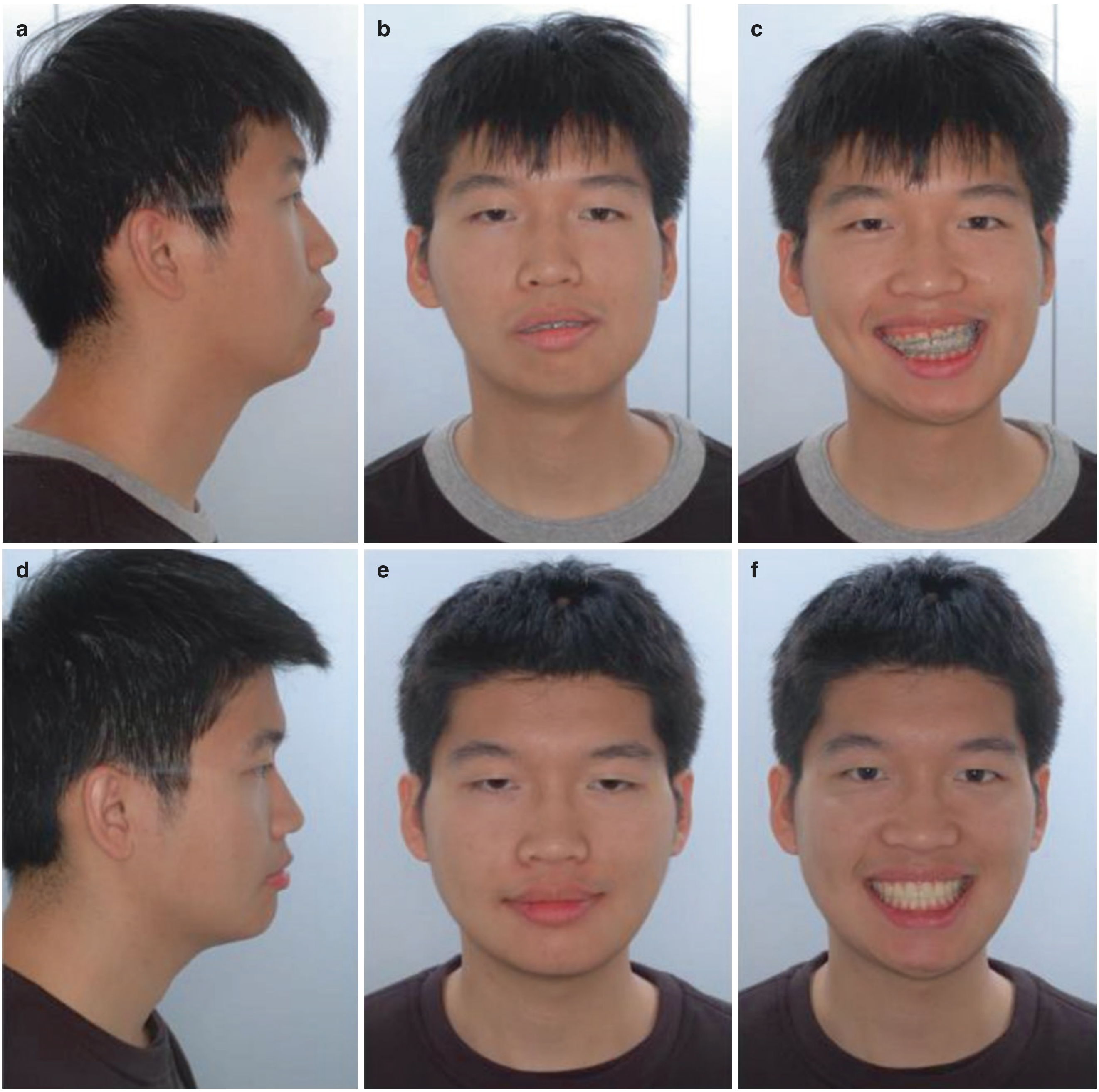

Fig. 37.30 Clinical CASS example. (**a**, **b**, **c**) The first row shows the patient's deformity, unilateral (right) condylar hyperplasia. The second row (**d**, **e**, **f**) shows the postoperative outcome. (**g**, **h**, **i**) Preoperative CASS deformity, (**j**, **k**, **l**) surgical plan

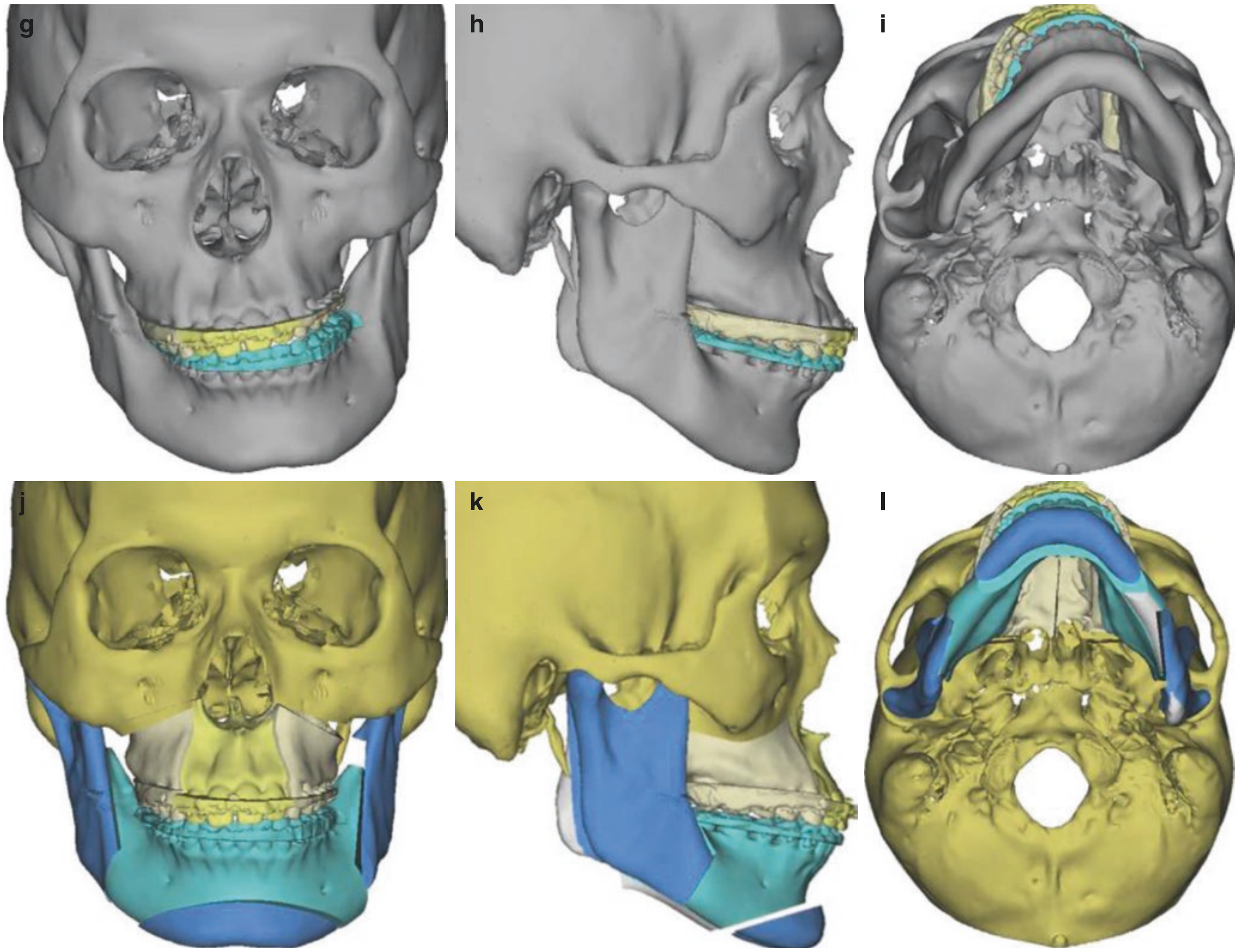

Fig. 37.30 (continued)

require preparation prior to surgery. In this section we discuss how to prepare for the execution of a surgical plan.

Jaw osteotomies can give rise to two types of movable bone segments: dentate and non-dentate—with teeth and without. The type and number of segments produced depends on the location of the osteotomies. For example, in a genioplasty, one movable non-dentate segment is created. In a standard LeFort I osteotomy, a single dentate segment is produced. In mandibular rami osteotomies, three segments are created: one distal and two proximal, the distal is dentate, and the proximals are not.

During orthognathic surgery, a surgeon must relocate all movable jaw segments (dentate and non-dentate). The new location of the dentate segments is established using *occlusal surgical splints*. These splints are arch-shaped removable plastic appliances that are placed between the occlusal surfaces of the upper and lower teeth to relocate and temporarily stabilize jaw segments.

There are two types of occlusal splints: *intermediate and final*. *Intermediate splints* are used exclusively in double-jaw surgery, a surgery that is done in sequence (one jaw, then the other). During surgery, the surgeon first cuts and moves one jaw, places it in its new alignment, and fixates it. Then, the same is done on the other jaw. Intermediate occlusal splints are devices that relate the dentate segments of one jaw—first to have surgery—to the unmoved dentate segment of the other.

Final splints are splints that place dentate segments into *final occlusion*—the planned occlusion at the end of surgery. Final splints are needed when the final occlusion is unstable (prone to slipping) or when interdental osteotomies are used to segment the dental arch (e.g., three-piece LeFort I, Hofer

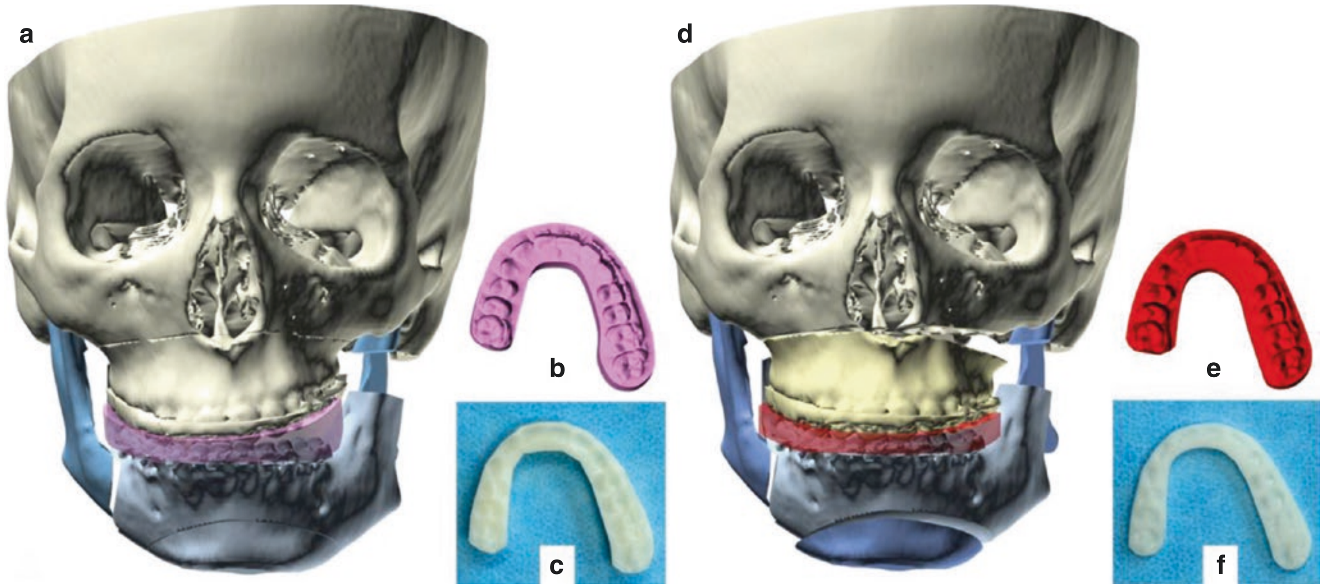

Fig. 37.31 Intermediate occlusal splint (**a**, **b**, and **c**). Final occlusal splint (**d**, **e**, and **f**)

osteotomy). They are used in single- and double-jaw surgery.

In CASS, both types of splints—intermediate and final—are designed in the computer and then fabricated using rapid prototyping techniques [4, 25, 26, 65, 66]. To create an intermediate splint, the computer model is made to show the first jaw in its final alignment and the second jaw in its original condition. If present, collision (i.e., overlap) between upper and lower teeth is avoided by rotating the mandible open. Next, a three-dimensional arch-shaped pattern is placed between the upper and lower teeth; and the teeth are subtracted from the pattern. The resultant digital splint is fabricated by rapid prototyping (Fig. 37.31 a,b,c). A nontoxic sterilizable material is used for this purpose. A final splint is created in a similar fashion with the exception that, for this splint, the computer model is placed in final occlusion—final outcome (Fig. 37.31 d,e,f).

When double-jaw surgery involves the segmentation of the dento-alveolus of the first jaw, the use of separate—intermediate and final—splints is time-consuming. In such a case, a surgeon performs the following steps:

1. Cuts the first jaw, creating two or more dento-osseous segments
2. Locates and wires each of the dento-osseous segments into the *intermediate splint*
3. Places the splint on the opposite jaw (uncut jaw)
4. Wires upper and lower teeth together, using maxillo-mandibular wires
5. Fixates the first jaw, using plates and screws
6. Removes the wires and the intermediate splint
7. Cuts the second jaw
8. Wires each of the dento-osseous segments of the first jaw into the *final splint*
9. Places the dentate segment of the second jaw into the final splint
10. Wires upper and lower teeth together, using maxillo-mandibular wires
11. Fixates the second jaw

In these cases, using a *sandwich occlusal splint* rather than separate intermediate and final splints simplifies and shortens surgery. A *sandwich occlusal splint* is a two-part splint made by interlocking final and intermediate splints. This splint is fabricated in the following fashion: first, a regular final splint is fabricated with both jaws in their final position (Fig. 37.32a). Next, the second jaw having surgery is rendered in its original form (uncut), while the final splint is left on the segmented first jaw. Then, the bite is opened to avoid collisions, and the intermediate splint is fashioned between the final splint and the uncut jaw (Fig. 37.32b).

When using a sandwich splint, the surgeon:

1. Cuts the first jaw, creating two or more dento-osseous segments
2. Locates and wires each of the dento-osseous segments into the *final splint*
3. Places the intermediate splint between the final splint and the opposite jaw
4. Wires upper and lower teeth together, using maxillo-mandibular wires
5. Fixates the first jaw, using plates and/or screws
6. Removes the wires and intermediate splint
7. Cuts the second jaw

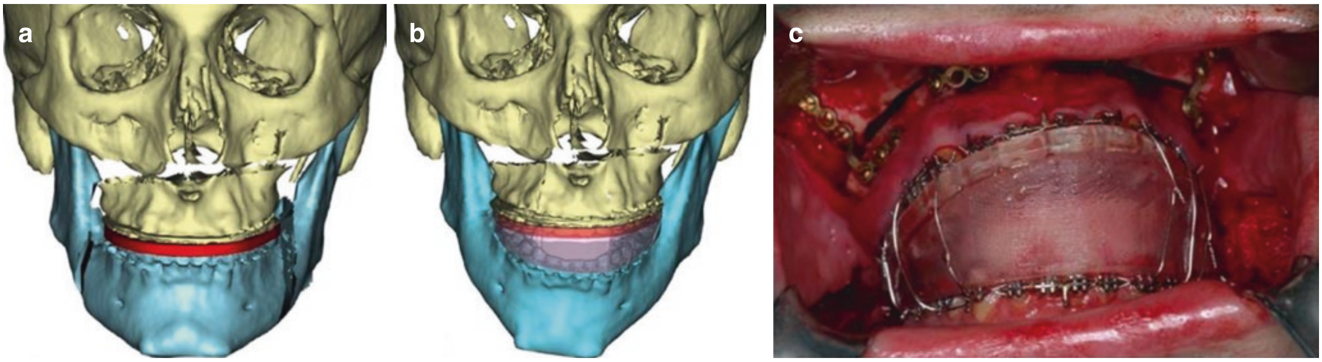

Fig. 37.32 Sandwich occlusal splint

8. Places the dentate segment of the second jaw into the final splint
9. Wires upper and teeth together, using maxillomandibular wires
10. Fixates the second jaw

A *sandwich splint* eliminates one step: wiring each of the dentoalveolar segments (of the first jaw) into the intermediate splint, a task that is tedious and time-consuming. Figure 37.32c shows the intraoperative use of a sandwich splint. The photo shows the final splint, stabilizing three maxillary dentoalveolar segments, and the intermediate splint—located between the final splint and the lower jaw—relocating the upper jaw.

Occlusal splints place dentate-osteotomy segments into planned alignment. These devices are all one needs to reposition the dentate segments of the mandible, but they are insufficient for the maxilla. In maxillary surgery, the upper jaw is articulated against the mandible, a movable bone. A cut upper jaw moves even when wired to the mandible. So in maxillary surgery, one needs additional methods to set the maxilla into final alignment. In addition to using splints, surgeons restrict mandibular movements to rotation by placing the mandible in centric relationship and control vertical maxillary position using intraoperative measurements.

At surgery, before cutting the upper jaw, a surgeon inserts a K-wire into the nasal bones. From this external reference, he establishes the baseline vertical maxillary position by measuring the distance between the K-wire and the *upper incisal midpoint*. Next, he calculates the target vertical position by adding or subtracting the planned vertical change to or from the baseline measurement. After mobilizing the maxilla and wiring it to the mandible, he sets the mandible into centric relationship and rotates the maxillomandibular complex up or down until the upper incisal midpoint reaches the target distance. In this position, he fixates the maxilla.

In orthognathic surgery, non-dentate segments arise in the mandible after osteotomies of the rami or chin. The non-dentate proximal segments of mandibular ramus osteotomies (sagittal split, vertical, or inverted L) reach their final alignment when the relationship between the proximal and distal segments seen in CASS is reproduced at surgery.

During the operation, the surgeon looks at pictures of the planned outcome showing the relationship between the proximal and distal segments. At the same time, he manipulates a given proximal segment until this relationship is attained. This may involve resecting the bone in areas of overlap and/or the creation of gaps between the segments. CASS facilitates these maneuvers by mapping and quantifying these areas ahead of time.

During genioplasty, surgeons can relocate the chin segment, freehand or with templates. The freehand method is the same as described above for the mandibular proximal segment: the surgeon attempts to reproduce on the patient, what she sees in CASS. The template method uses surgical templates to place the chin in its new alignment. Surgical templates are removable appliances that relocate and stabilize a non-dentate bony segment. They relate the planned position of the movable segment to adjacent segments.

Investigators at Houston Methodist Hospital in Texas developed the first chin template system (Fig. 37.33) [4, 26]. This system uses two templates: a marking template and a positioning template. Both relate the chin to the lower teeth. The marking template (Fig. 37.33a, b) is used first. It marks the position and orientation of two pilot holes that are drilled on each side of the chin. After completion of the osteotomy, a surgeon places the positioning template (Fig. 37.33c, d) on the lower teeth and aligns the chin to template. The chin is then temporarily fixated to the template using two 2 mm in diameter screws. The screws are inserted through the template into the previously drilled pilot holes. Next, a surgeon installs a chin plate to stabilize the chin permanently. Finally, the positioning template is removed.

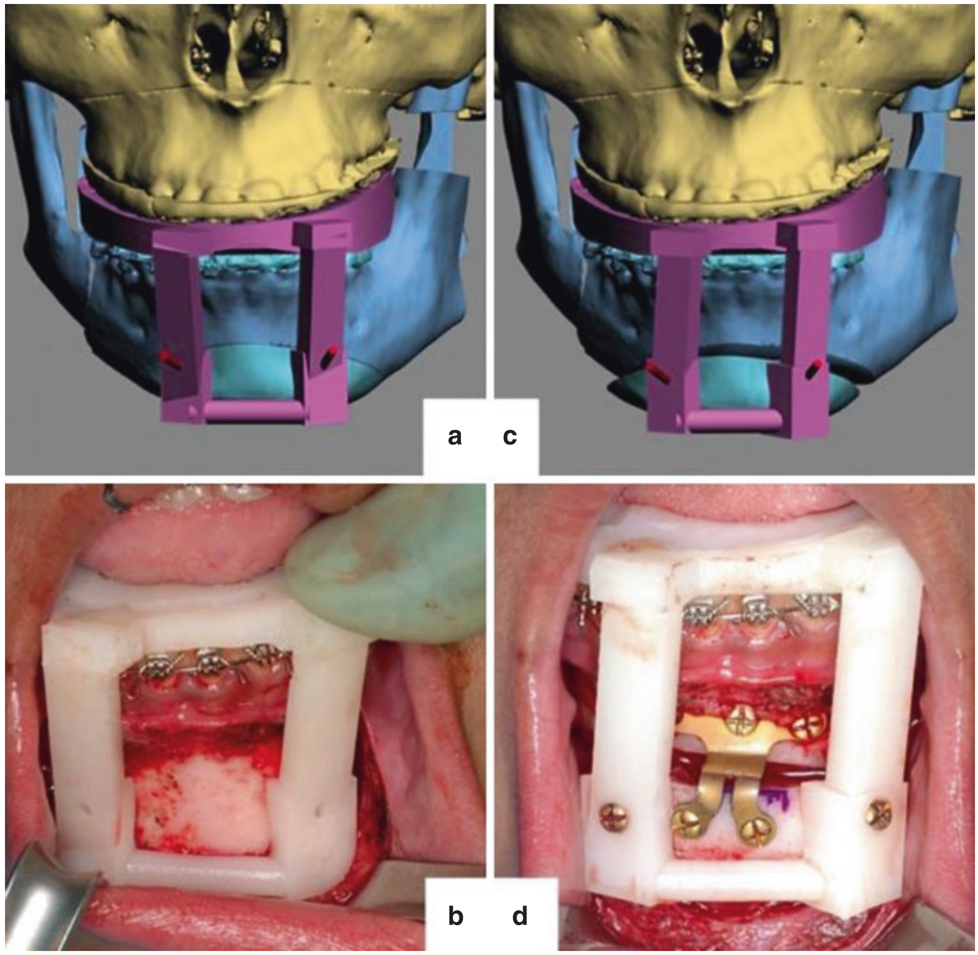

Fig. 37.33 Chin templates (**a**) virtual marking template, (**b**) intraoperative marking template, (**c**) virtual positioning template, (**d**) intraoperative positioning template

Conclusion

Treatment planning for orthognathic surgery is a complex process involving evaluation, assessment, planning to develop the correct surgical plan for each patient. Using Computer Assisted Surgical Simulation (CASS) has allowed greatly improved visualization, diagnosis, and surgical procedures using 3D printed surgical splints, cutting, positioning and drill guides. We have presented our comprehensive approach to orthognathic examination and treatment planning, which will continue to evolve as new technologies develop.

References

1. Zelditch M. Geometric morphometrics for biologist: a primer. Amsterdam: Elsevier; 2012.
2. Gateno J, Xia JJ, Teichgraeber JF. New methods to evaluate craniofacial deformity and to plan surgical correction. Semin Orthod. 2011;17:225–34.
3. Gateno J, Xia JJ, Teichgraeber JF. New 3-dimensional cephalometric analysis for orthognathic surgery. J Oral Maxillofac Surg. 2011;69:606–22.
4. Xia JJ, Gateno J, Teichgraeber JF. New clinical protocol to evaluate craniomaxillofacial deformity and plan surgical correction. J Oral Maxillofac Surg. 2009;67:2093–106.
5. Schatz EC, Xia JJ, Gateno J, English JD, Teichgraeber JF, Garrett FA. Development of a technique for recording and transferring natural head position in 3 dimensions. J Craniofac Surg. 2010;21:1452–5.
6. Xia JJ, McGrory JK, Gateno J, et al. A new method to orient 3-dimensional computed tomography models to the natural head position: a clinical feasibility study. J Oral Maxillofac Surg. 2011;69:584–91.
7. Proffit WR, Fields HW Jr, Ackerman JL, Bailey LJ, Tulloch JFC. Contemporary Orthodontics. 3rd ed. St. Louis: Mosby; 2000.
8. Epker BN, Stella JP, Fish LC. Dentofacial Deformities. St. Louis: Mosby; 1995.
9. Bell WH, editor. Surgical Correction of Dentofacial Deformities. Philadelphia: W.B. Saunders; 1980.
10. Bell WH, editor. Modern Practice in Orthognathic and Reconstructive Surgery. Philadelphia: W.B. Saunders; 1992.
11. Vig RG, Brundo GC. The kinetics of anterior tooth display. J Prosthet Dent. 1978;39:502–4.
12. Van der Geld P, Oosterveld P, Kuijpers-Jagtman AM. Age-related changes of the dental aesthetic zone at rest and during spontaneous smiling and speech. Eur J Orthod. 2008;30:366–73.
13. Tjan AH, Miller GD, The JG. Some esthetic factors in a smile. J Prosthet Dent. 1984;51:24–8.
14. Sarver DM. The importance of incisor positioning in the esthetic smile: the smile arc. Am J Orthod Dentofac Orthop. 2001;120:98–111.

15. Sarver DM, Ackerman MB. Dynamic smile visualization and quantification: part 2. Smile analysis and treatment strategies. Am J Orthod Dentofac Orthop. 2003;124:116–27.
16. Sarver DM, Ackerman MB. Dynamic smile visualization and quantification: part 1. Evolution of the concept and dynamic records for smile capture. Am J Orthod Dentofac Orthop. 2003;124:4–12.
17. Coslet JG, Vanarsdall R, Weisgold A. Diagnosis and classification of delayed passive eruption of the dentogingival junction in the adult. Alpha Omegan. 1977;70:24–8.
18. Lele S. An Invariant Approach to Statistical Analysis of Shape. Boca Raton: Chapman & Hall/CRC; 2001.
19. Kumar KP, Tamizharasi S. Significance of curve of Spee: an orthodontic review. J Pharm Bioallied Sci. 2012;4:S323–8.
20. Ash MM, Ramfjord SP. Occlusion. 4th ed. Philadelphia: W.B. Saunders; 1995.
21. Gateno J, Xia JJ, Teichgraeber JF. Effect of facial asymmetry on 2-dimensional and 3-dimensional cephalometric measurements. J Oral Maxillofac Surg. 2011;69:655–62.
22. Swennen GR, Mollemans W, Schutyser F. Three-dimensional treatment planning of orthognathic surgery in the era of virtual imaging. J Oral Maxillofac Surg. 2009;67:2080–92.
23. Swennen GR, Schutyser F, Barth EL, De Groeve P, De Mey A. A new method of 3-D cephalometry part I: the anatomic Cartesian 3-D reference system. J Craniofac Surg. 2006;17:314–25.
24. Xia JJ, Shevchenko L, Gateno J, et al. Outcome study of computer-aided surgical simulation in the treatment of patients with craniomaxillofacial deformities. J Oral Maxillofac Surg. 2011;69:2014–24.
25. Xia JJ, Gateno J, Teichgraeber JF. Three-dimensional computer-aided surgical simulation for maxillofacial surgery. Atlas Oral Maxillofac Surg Clin North Am. 2005;13:25–39.
26. Hsu SS, Gateno J, Bell RB, et al. Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. J Oral Maxillofac Surg. 2013;71:128–42.
27. Nadjmi N, Mommaerts MY, Abeloos JV, De Clercq CA. Prediction of mandibular autorotation. J Oral Maxillofac Surg. 1998;56:1241–7. discussion 7-8
28. Lemoine JJ, Xia JJ, Andersen CR, Gateno J, Buford W Jr, Liebschner MA. Geometry-based algorithm for the prediction of nonpathologic mandibular movement. J Oral Maxillofac Surg. 2007;65:2411–7.
29. Lemoine JJ, Xia JJ, Gateno J, Liebschner MA. Radiographic analysis for jaw motion normalization. J Oral Maxillofac Surg. 2005;63(7):961.
30. Perez D, Ellis E 3rd. Sequencing bimaxillary surgery: mandible first. J Oral Maxillofac Surg. 2011;69:2217–24.
31. Gateno J, Xia J, Teichgraeber JF, Rosen A. A new technique for the creation of a computerized composite skull model. J Oral Maxillofac Surg. 2003;61:222–7.
32. Santler G. 3-D COSMOS: a new 3-D model based computerised operation simulation and navigation system. J Craniomaxillofac Surg. 2000;28:287–93.
33. Santler G, Karcher H, Gaggl A, Kern R. Stereolithography versus milled three-dimensional models: comparison of production method, indication, and accuracy. Comput Aided Surg. 1998;3:248–56.
34. Krishnan R, Hermann E, Wolff R, Zimmermann M, Seifert V, Raabe A. Automated fiducial marker detection for patient registration in image-guided neurosurgery. Comput Aided Surg. 2003;8:17–23.
35. Chang YB, Xia JJ, Gateno J, Xiong Z, Zhou X, Wong ST. An automatic and robust algorithm of reestablishment of digital dental occlusion. IEEE Trans Med Imaging. 2010;29:1652–63.
36. Swennen GR, Barth EL, Eulzer C, Schutyser F. The use of a new 3D splint and double CT scan procedure to obtain an accurate anatomic virtual augmented model of the skull. Int J Oral Maxillofac Surg. 2007;36:146–52.
37. Besl PJ, McKay ND. A method for registration of 3-D shapes. IEEE Trans Pattern Anal Mach Intell. 1993;14:239–56.
38. Damstra J, Fourie Z, Ren Y. Simple technique to achieve a natural position of the head for cone beam computed tomography. Br J Oral Maxillofac Surg. 2010;48:236–8.
39. Xia J, Samman N, Yeung RW, et al. Three-dimensional virtual reality surgical planning and simulation workbench for orthognathic surgery. Int J Adult Orthodon Orthognath Surg. 2000;15:265–82.
40. Xia J, Ip HH, Samman N, et al. Computer-assisted three-dimensional surgical planning and simulation: 3D virtual osteotomy. Int J Oral Maxillofac Surg. 2000;29:11–7.
41. Chang YB, Xia JJ, Gateno J, et al. In vitro evaluation of new approach to digital dental model articulation. J Oral Maxillofac Surg. 2012;70:952–62.
42. Xia JJ, Chang YB, Gateno J, Xiong Z, Zho X. Automated digital dental articulation. Med Image Comput Comput Assist Interv. 2010;13:278–86.
43. Hiew LT, Ong SH, Foong KWC. Optimal occlusion of teeth. In: 9th International Conference on Control, Automation, Robotics and Vision, ICARCV'06 2006. IEEE; 2006. p. 1–5.
44. DeLong R, Ko CC, Anderson GC, Hodges JS, Douglas WH. Comparing maximum intercuspal contacts of virtual dental patients and mounted dental casts. J Prosthet Dent. 2002;88:622–30.
45. Nadjmi N, Mollemans W, Daelemans A, Van Hemelen G, Schutyser F, Berge S. Virtual occlusion in planning orthognathic surgical procedures. Int J Oral Maxillofac Surg. 2010;39:457–62.
46. Rubin MB, Bodner SR. A three-dimensional non-linear model for dissipative response of soft tissue. Int J Solids Struct. 2002;39:5981–99.
47. Barbarino GG, Jabareen M, Trzewik J, Nkengne A, Stamatas G, Mazza E. Development and validation of a three-dimensional finite element model of the face. J Biomech Eng. 2009;131:041006.
48. Meller S, Nkenke E, Kalender WA. Statistical face models for the prediction of soft-tissue deformations after orthognathic osteotomies. In: MICCAI 2005. Lecture notes in computer science, vol. 3750. Berlin: Springer; 2005. p. 443–450.
49. Keeve E, Girod S, Kikinis R, Girod B. Deformable modeling of facial tissue for craniofacial surgery simulation. Comput Aided Surg. 1998;3:228–38.
50. Xia J, Ip HH, Samman N, et al. Three-dimensional virtual-reality surgical planning and soft-tissue prediction for orthognathic surgery. IEEE Trans Inf Technol Biomed. 2001;5:97–107.
51. Xia J, Samman N, Yeung RW, et al. Computer-assisted three-dimensional surgical planing and simulation. 3D soft tissue planning and prediction. Int J Oral Maxillofac Surg. 2000;29:250–8.
52. Nedel LP, Thalmann D. Real time muscle deformations using mass-spring systems. In: Proceedings of the computer graphics international, Hannover, Germany. IEEE; 1998. p. 156–166.
53. Chen F, Gu L, Huang P, Zhang J, Xu J. Soft tissue modeling using nonlinear mass spring and simplified medial representation. Conf Proc IEEE Eng Med Biol Soc. 2007;2007:5083–6.
54. Maal TJ, Plooij JM, Rangel FA, Mollemans W, Schutyser FA, Berge SJ. The accuracy of matching three-dimensional photographs with skin surfaces derived from cone-beam computed tomography. Int J Oral Maxillofac Surg. 2008;37:641–6.
55. Cover SA, Ezquerra NF, O'Brien JF. Interactively deformable models for surgery simulation. IEEE Comput Graph Appl. 1993;13:68–75.
56. Marchetti C, Bianchi A, Bassi M, Gori R, Lamberti C, Sarti A. Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU). J Craniofac Surg. 2006;17:661–7. discussion 668
57. Marchetti C, Bianchi A, Bassi M, Gori R, Lamberti C, Sarti A. Mathematical modeling and numerical simulation in maxillofacial virtual surgery. J Craniofac Surg. 2007;18:826–32.

58. Gori R, Sarti A, Lamberti C, Fares JE, Marchetti C. Maxillo-facial virtual surgery from 3D CT images. Bioengineering Science and Supercomputing at CINECA report. 2001.
59. Binucci MM, Lamberti C, Gori R, Montagna L, Sarti A. An integrated system for maxillo-facial surgery simulation. In: CARS 2002 Computer Assisted Radiology and Surgery. Berlin: Springer; 2002.
60. Koch RM, Gross MH, Carls FR, von Buren DF, Frankhauser G, Parish YIH. Simulating facial surgery using finite element models. In: SIGGRAPH. New York: ACM; 1996. p. 421–428.
61. Mollemans W, Schutyser F, Nadjmi N, Maes F, Suetens P. Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation. Med Image Anal. 2007;11:282–301.
62. Mollemans W, Schutyser F, Van Cleynenbreugel J, Suetens P. Tetrahedral mass spring model for fast soft tissue deformation. In: 2003 international conference on surgery simulation and soft tissue modeling. Berlin: Springer; 2003. p. 145–154.
63. Bhatia SN, Leighton BC. A Manual of Facial Growth - A Computer Analysis of Longitudinal Cephalometric Growth Data. 1st ed. New York: Oxford University Press; 1993.
64. Downs WB. The role of cephalometrics in orthodontic case analysis and diagnosis. Am J Orthod. 1952;38:162–82.
65. Gateno J, Xia J, Teichgraeber JF, Rosen A, Hultgren B, Vadnais T. The precision of computer-generated surgical splints. J Oral Maxillofac Surg. 2003;61(7):814.
66. Xia JJ, Gateno J, Teichgraeber JF, et al. Accuracy of the computer-aided surgical simulation (CASS) system in the treatment of patients with complex craniomaxillofacial deformity: a pilot study. J Oral Maxillofac Surg. 2007;65:248–54.