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(54) **SYSTEMS AND METHODS FOR TREATMENT ANALYSIS BY TEETH MATCHING**

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(73) Assignee: **Align Technology, Inc.**, Santa Clara, CA (US)

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This patent is subject to a terminal disclaimer.

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A61C 11/00 (2006.01)
A61C 3/00 (2006.01)

(52) **U.S. Cl.** **433/213**; 433/24

(58) **Field of Classification Search** 433/24, 433/213

See application file for complete search history.

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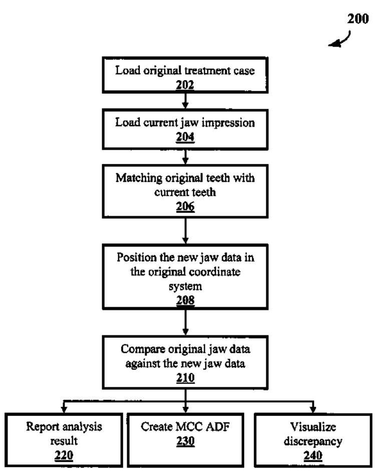
(57) **ABSTRACT**

Systems and methods are disclosed for matching computer models of two sets of teeth each having corresponding matching regions includes calculating a difference for two sets of teeth shapes; finding the position of one set of teeth with respect to the other set of teeth; calculating a positional difference of the corresponding teeth based on the matching regions; and finding a corrective path to bring one set of teeth to the other set of teeth.

26 Claims, 15 Drawing Sheets



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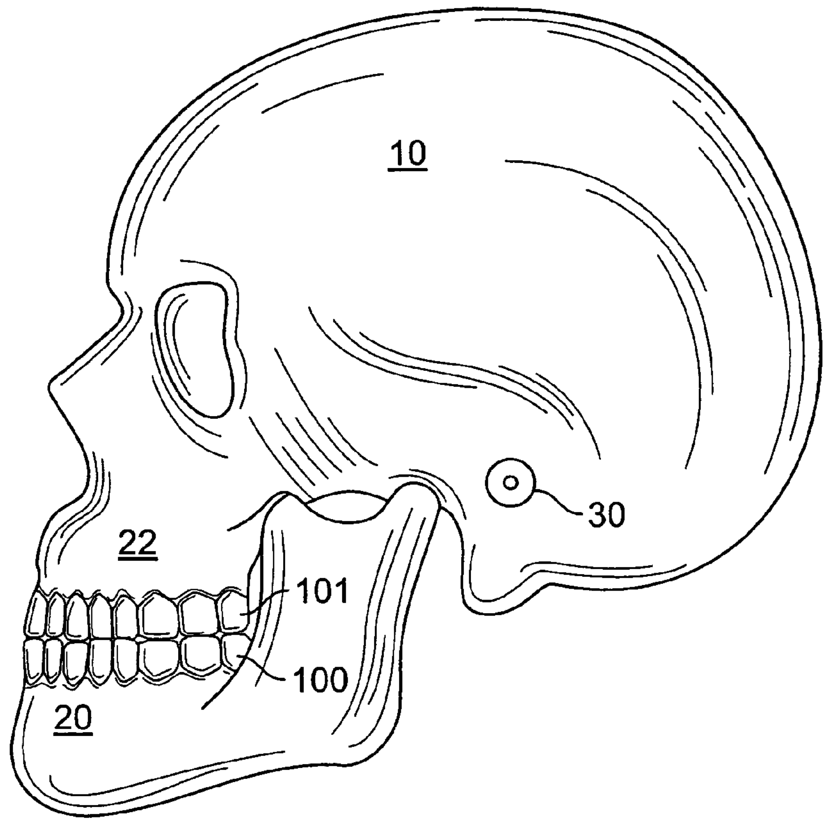


FIG. 1

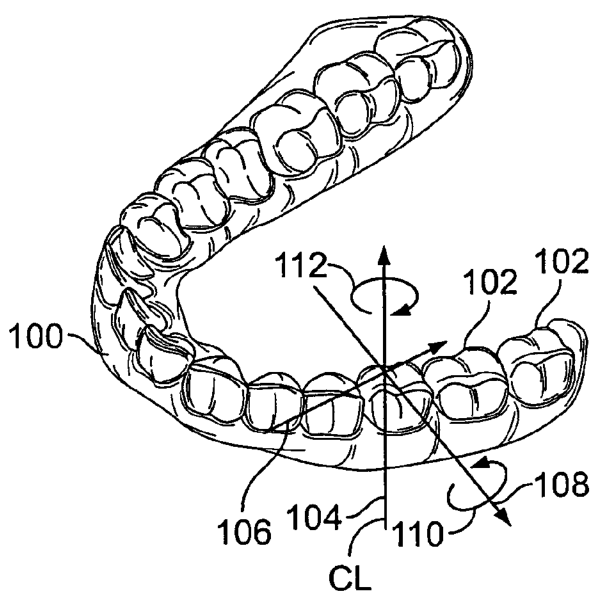


FIG. 2A

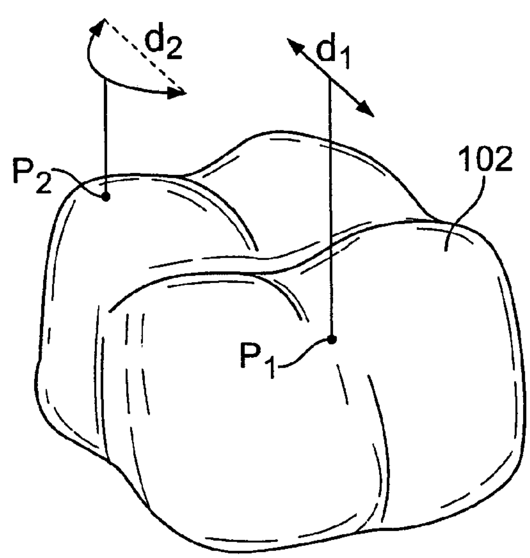


FIG. 2B

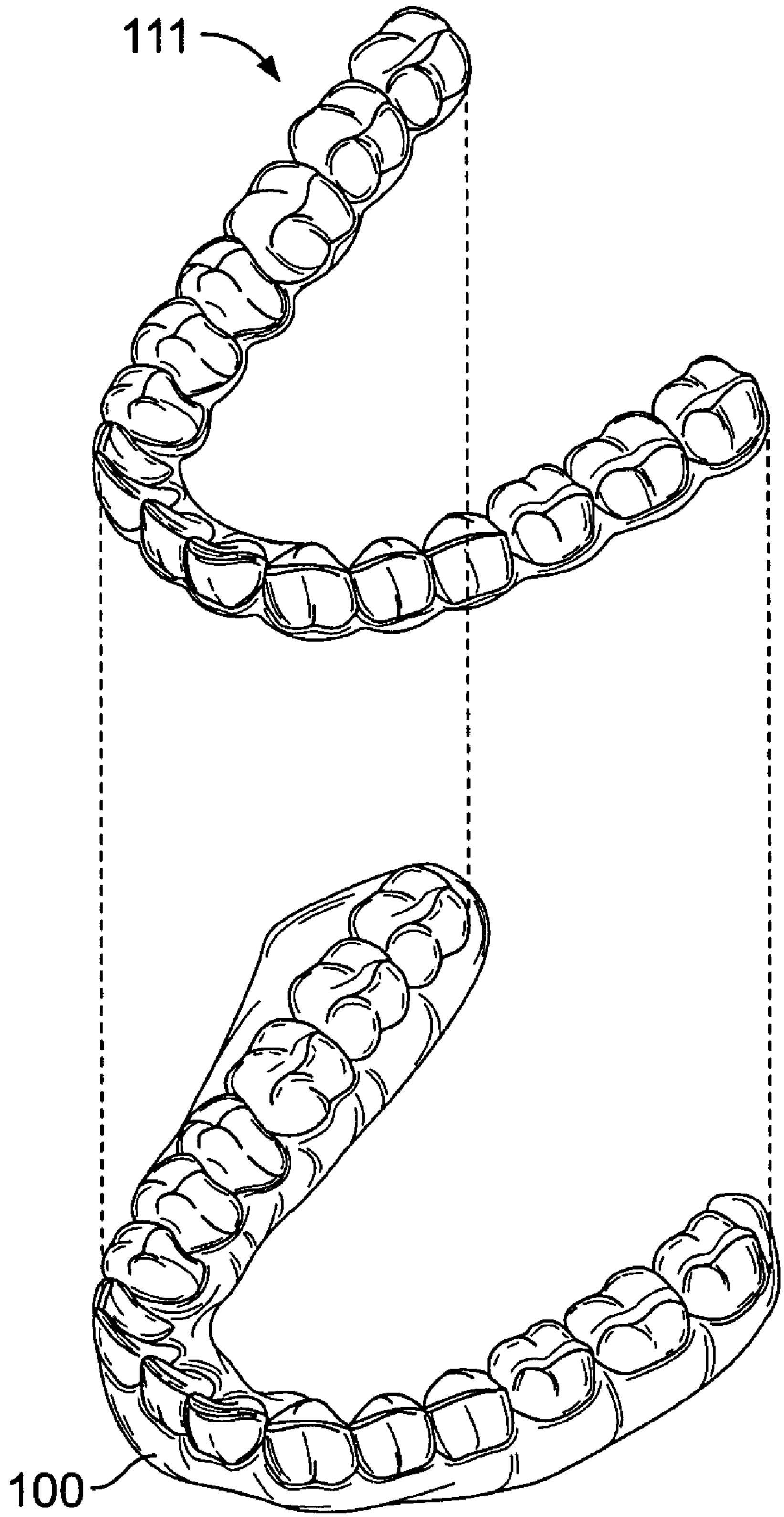


FIG. 2C

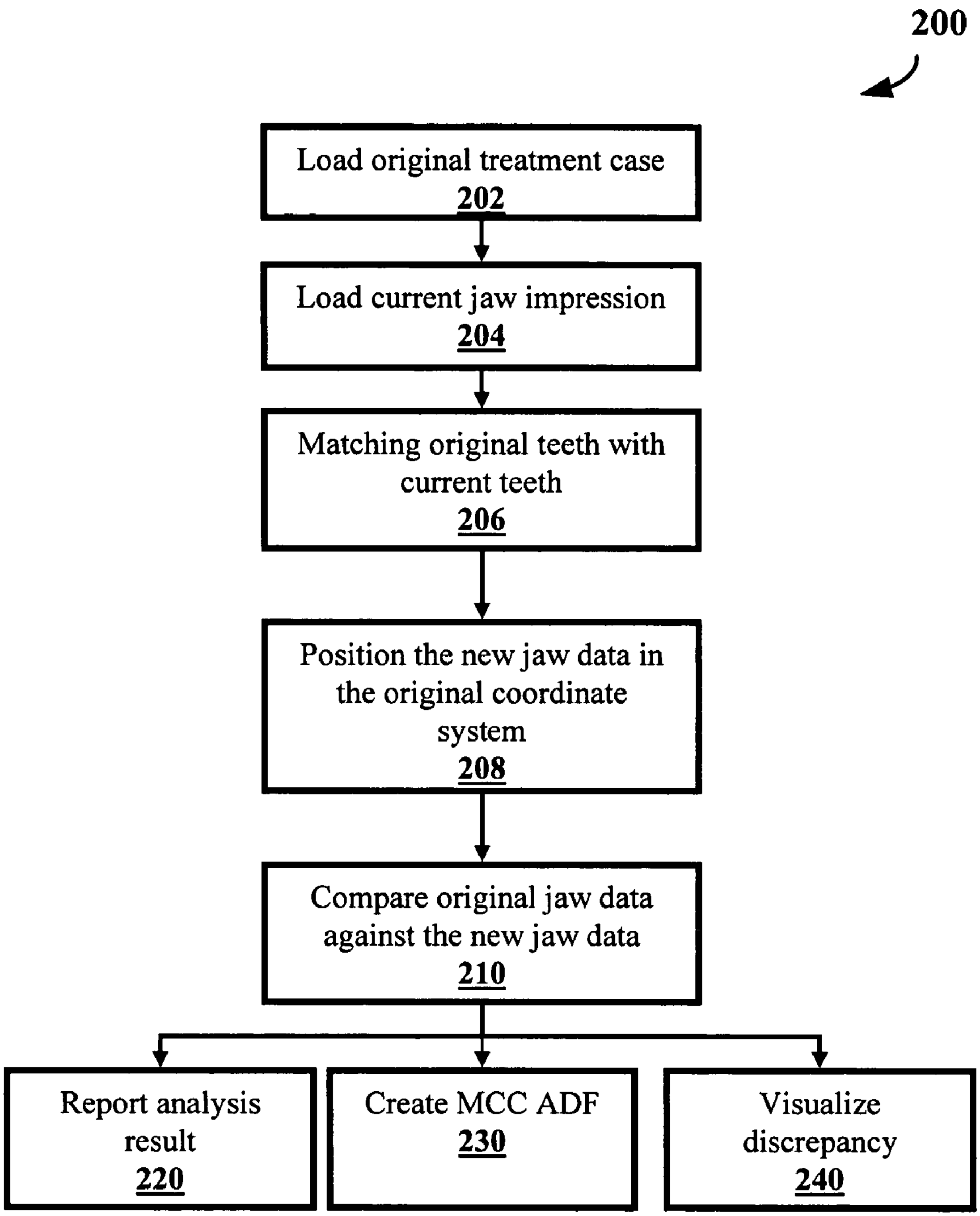

200
Load original treatment case
202
Load current jaw impression
204
Matching original teeth with current teeth
206
Position the new jaw data in the original coordinate system
208
Compare original jaw data against the new jaw data
210
Report analysis result
220
Create MCC ADF
230
Visualize discrepancy
240

FIG. 3

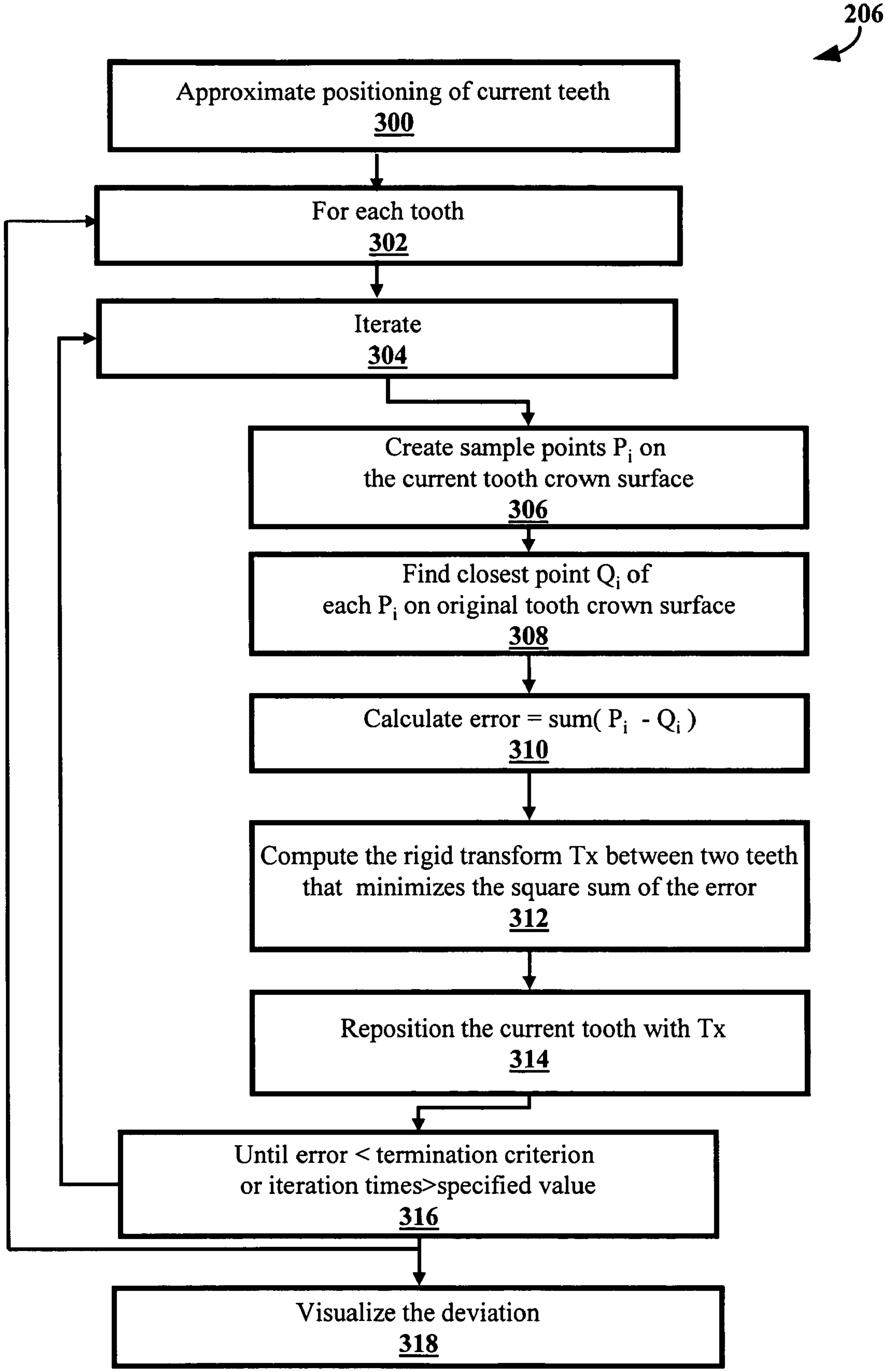

206
Approximate positioning of current teeth
300
For each tooth
302
Iterate
304
Create sample points P_i on the current tooth crown surface
306
Find closest point Q_i of each P_i on original tooth crown surface
308
Calculate error = sum(P_i - Q_i)
310
Compute the rigid transform Tx between two teeth that minimizes the square sum of the error
312
Reposition the current tooth with Tx
314
Until error < termination criterion or iteration times>specified value
316
Visualize the deviation
318

FIG. 4

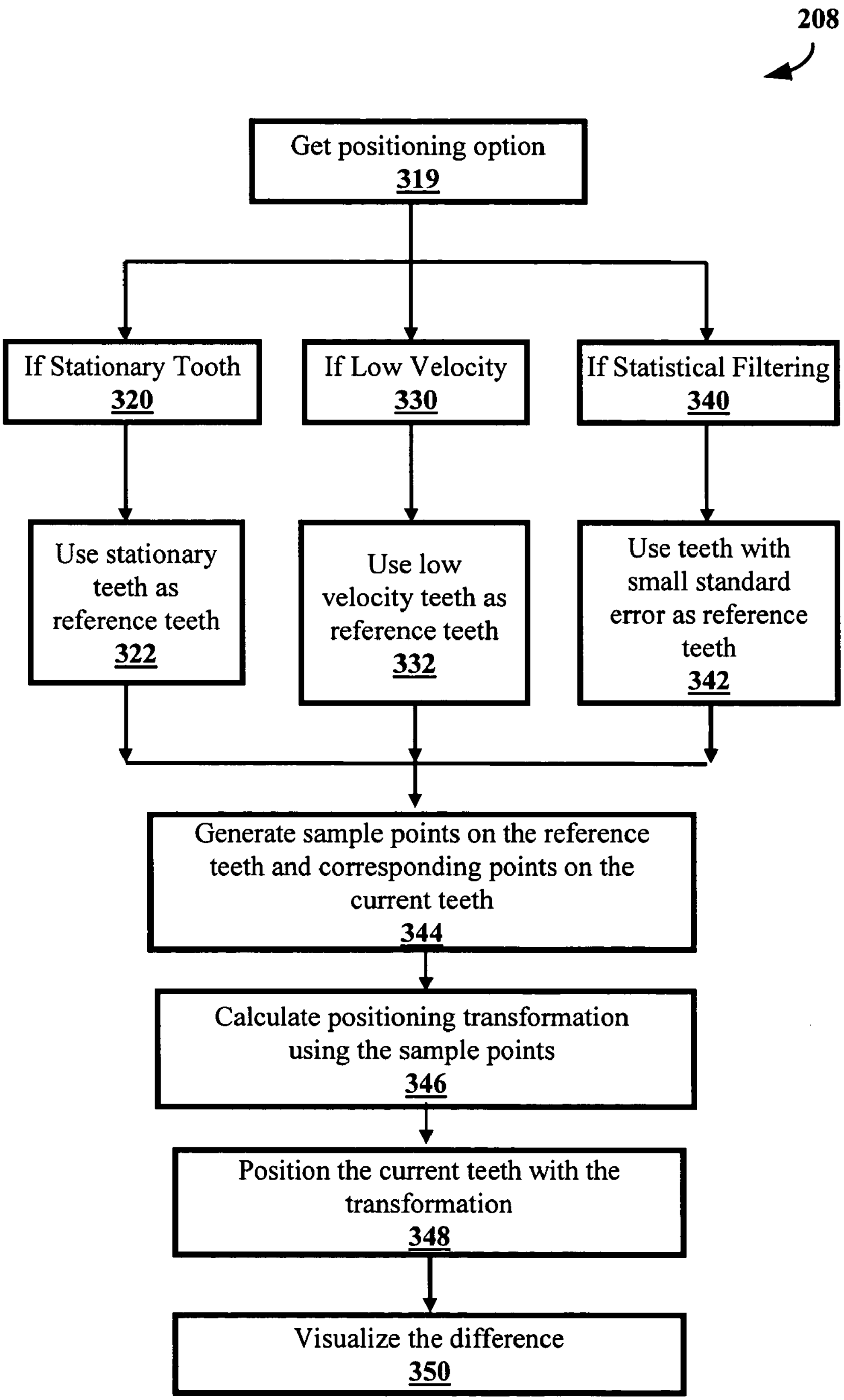

208
Get positioning option
319
If Stationary Tooth
320
If Low Velocity
330
If Statistical Filtering
340
Use stationary teeth as reference teeth
322
Use low velocity teeth as reference teeth
332
Use teeth with small standard error as reference teeth
342
Generate sample points on the reference teeth and corresponding points on the current teeth
344
Calculate positioning transformation using the sample points
346
Position the current teeth with the transformation
348
Visualize the difference
350

FIG. 5

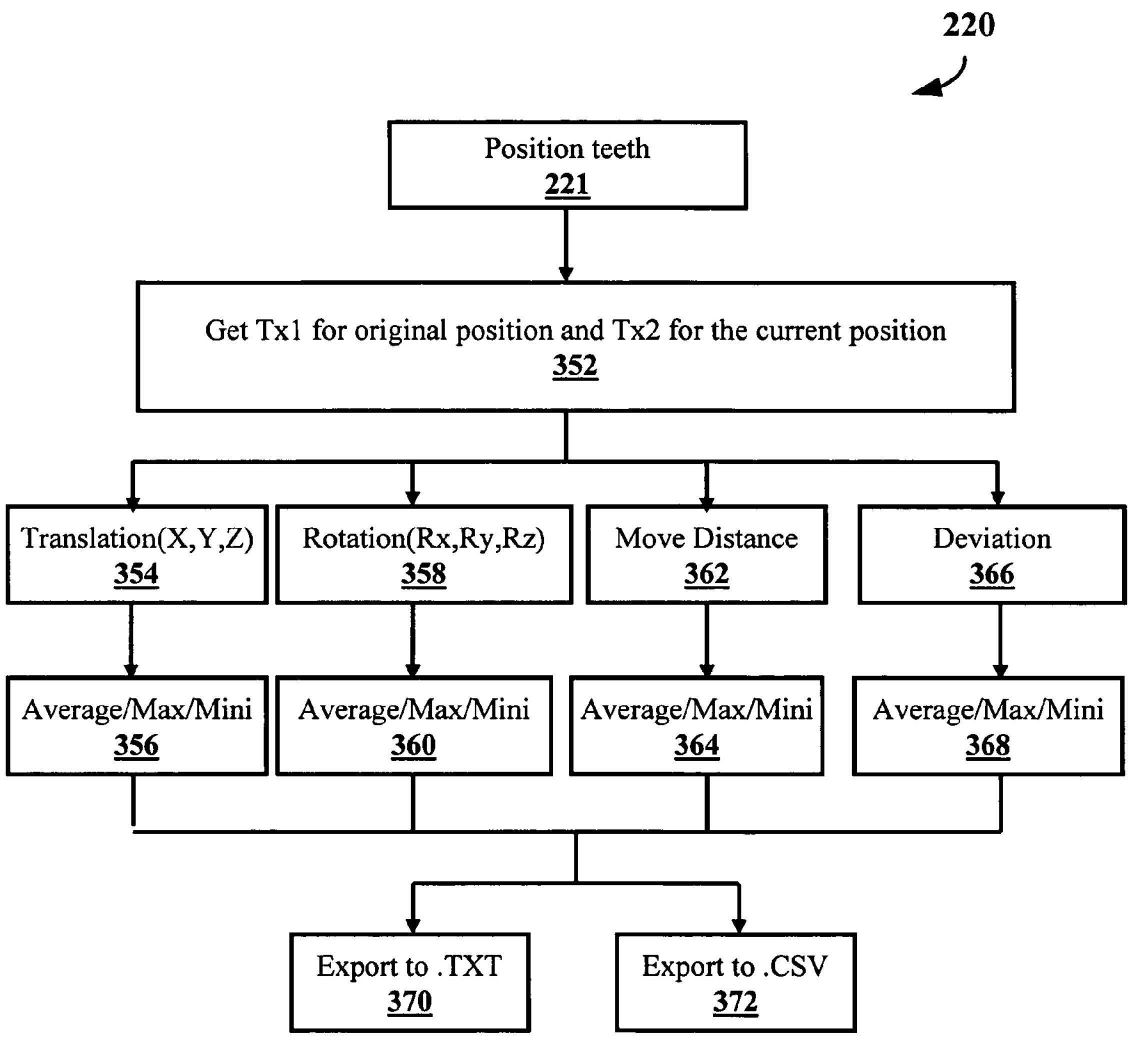

220
Position teeth
221
Get Tx1 for original position and Tx2 for the current position
352
Translation(X,Y,Z)
354
Rotation(Rx,Ry,Rz)
358
Move Distance
362
Deviation
366
Average/Max/Mini
356
Average/Max/Mini
360
Average/Max/Mini
364
Average/Max/Mini
368
Export to .TXT
370
Export to .CSV
372

FIG. 6

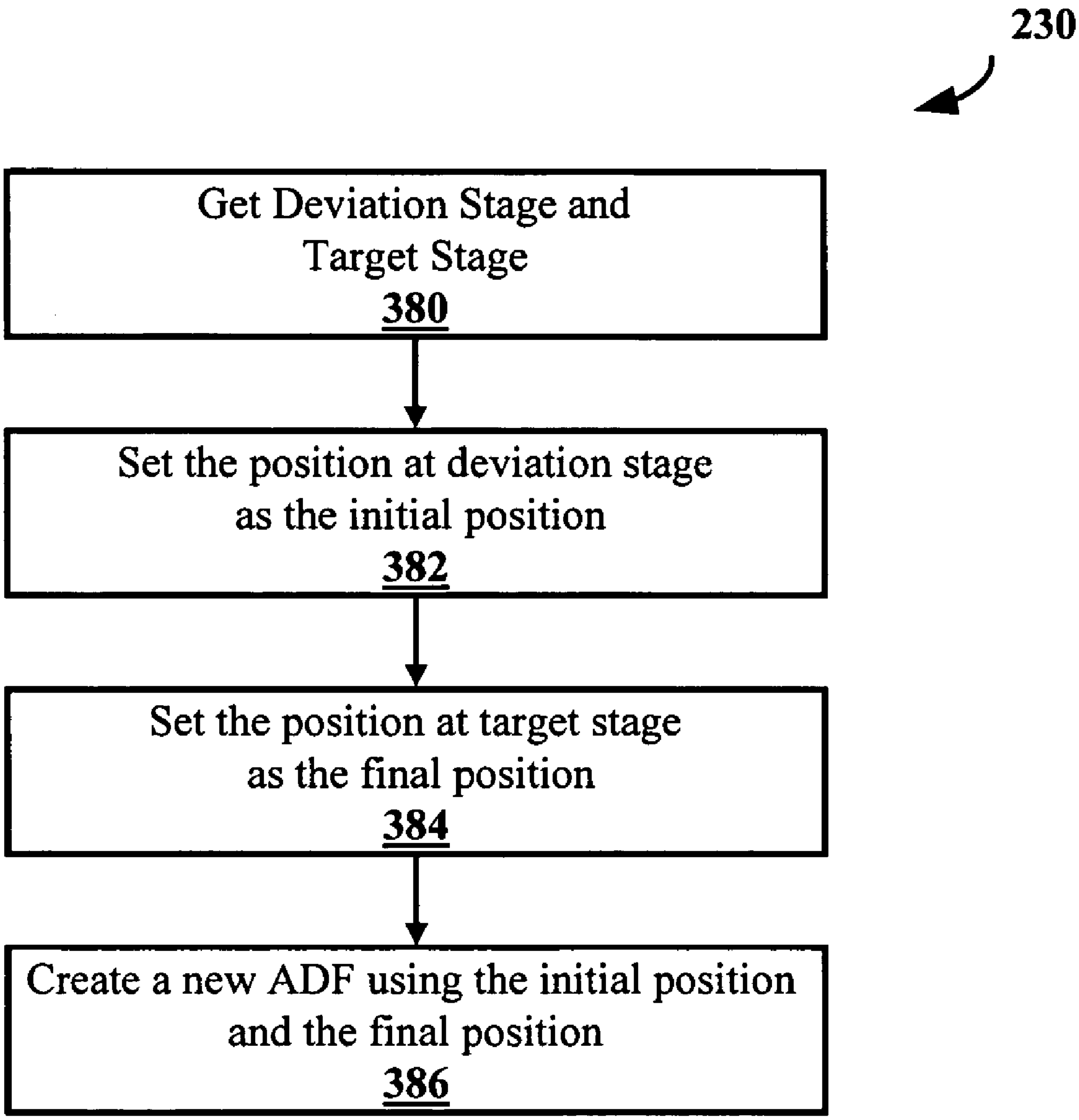

230
Get Deviation Stage and Target Stage
380
Set the position at deviation stage as the initial position
382
Set the position at target stage as the final position
384
Create a new ADF using the initial position and the final position
386

FIG. 7

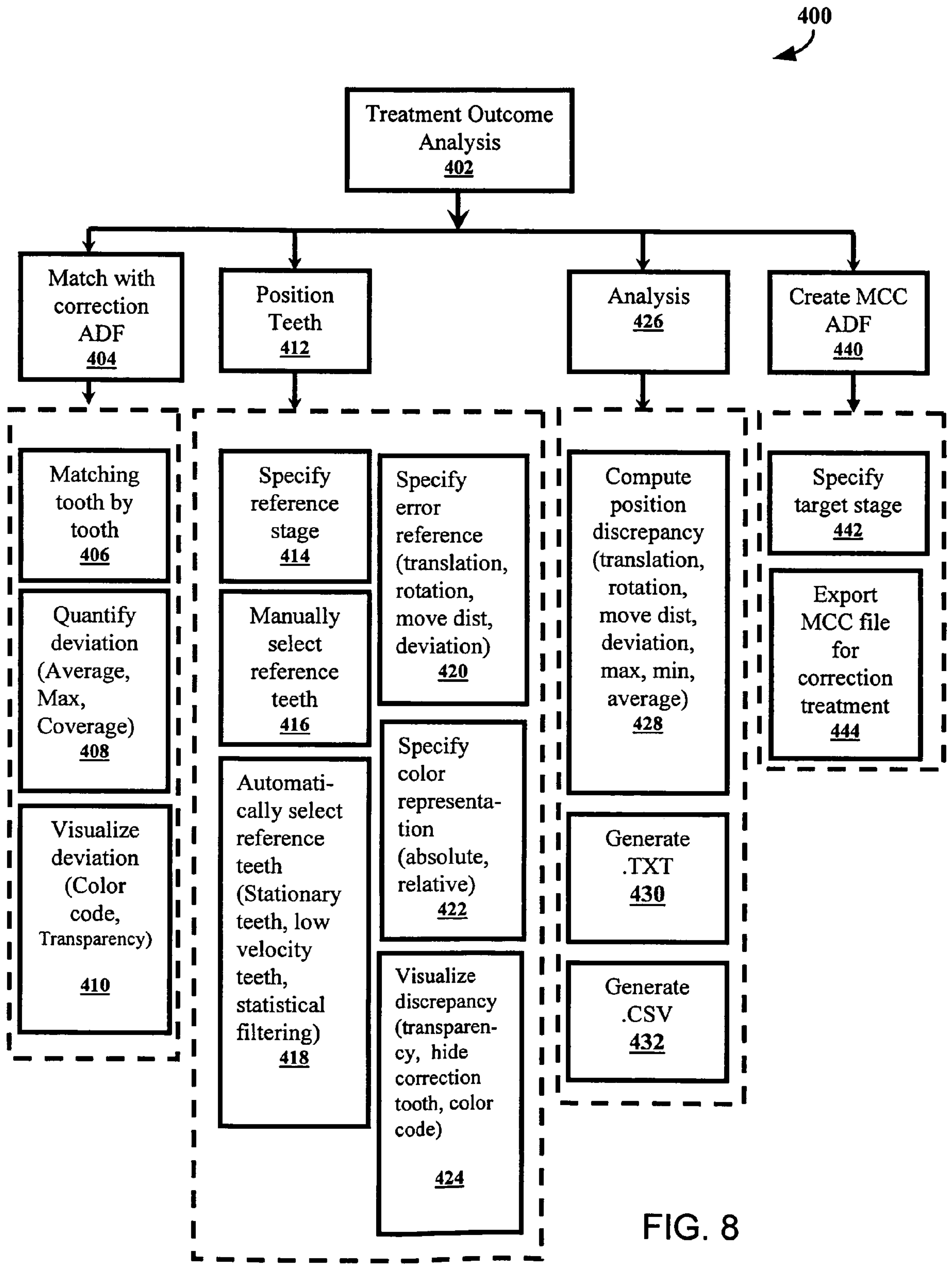

400
Treatment Outcome Analysis 402
Match with correction ADF 404
Position Teeth 412
Analysis 426
Create MCC ADF 440
Matching tooth by tooth 406
Quantify deviation (Average, Max, Coverage) 408
Visualize deviation (Color code, Transparency) 410
Specify reference stage 414
Manually select reference teeth 416
Automatically select reference teeth (Stationary teeth, low velocity teeth, statistical filtering) 418
Specify error reference (translation, rotation, move dist, deviation) 420
Specify color representation (absolute, relative) 422
Visualize discrepancy (transparency, hide correction tooth, color code) 424
Compute position discrepancy (translation, rotation, move dist, deviation, max, min, average) 428
Generate .TXT 430
Generate .CSV 432
Specify target stage 442
Export MCC file for correction treatment 444

FIG. 8

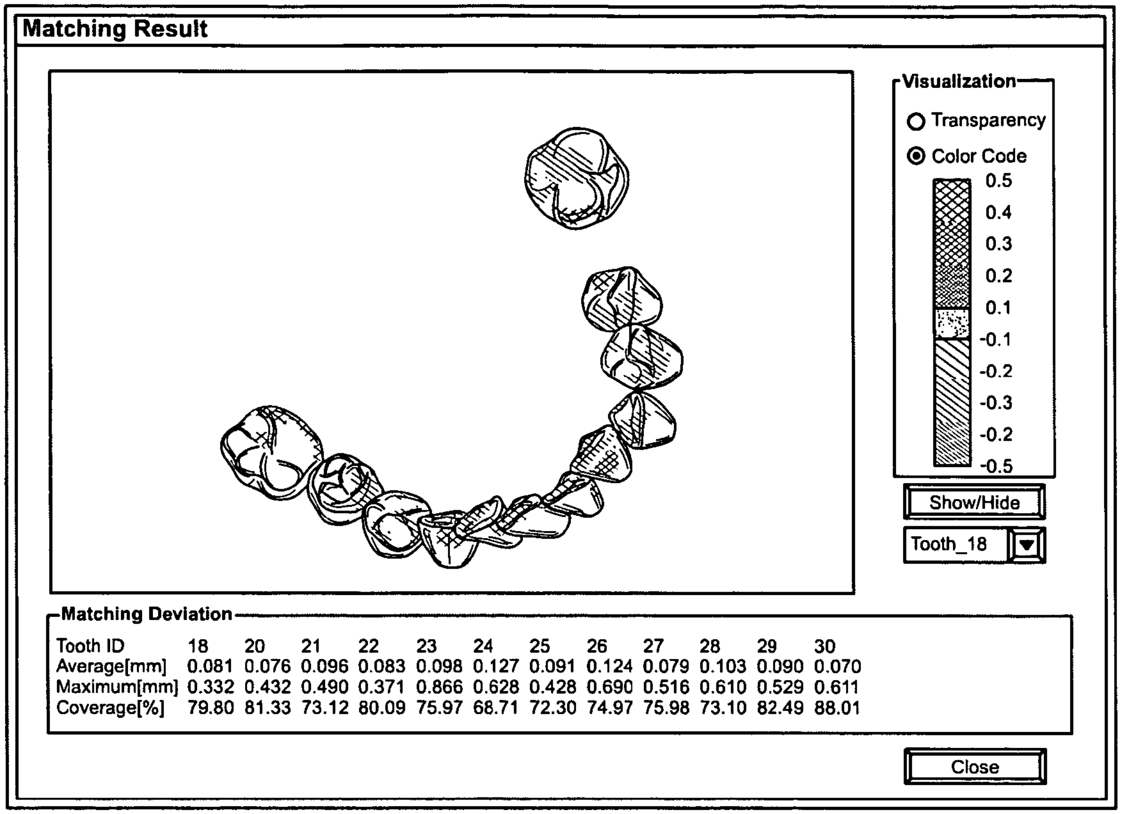

Matching Result
Visualization
Transparency
Color Code
0.5
0.4
0.3
0.2
0.1
-0.1
-0.2
-0.3
-0.2
-0.5
Show/Hide
Tooth_18
Matching Deviation
Tooth ID 18 20 21 22 23 24 25 26 27 28 29 30
Average[mm] 0.081 0.076 0.096 0.083 0.098 0.127 0.091 0.124 0.079 0.103 0.090 0.070
Maximum[mm] 0.332 0.432 0.490 0.371 0.866 0.628 0.428 0.690 0.516 0.610 0.529 0.611
Coverage[%] 79.80 81.33 73.12 80.09 75.97 68.71 72.30 74.97 75.98 73.10 82.49 88.01
Close

FIG. 9A

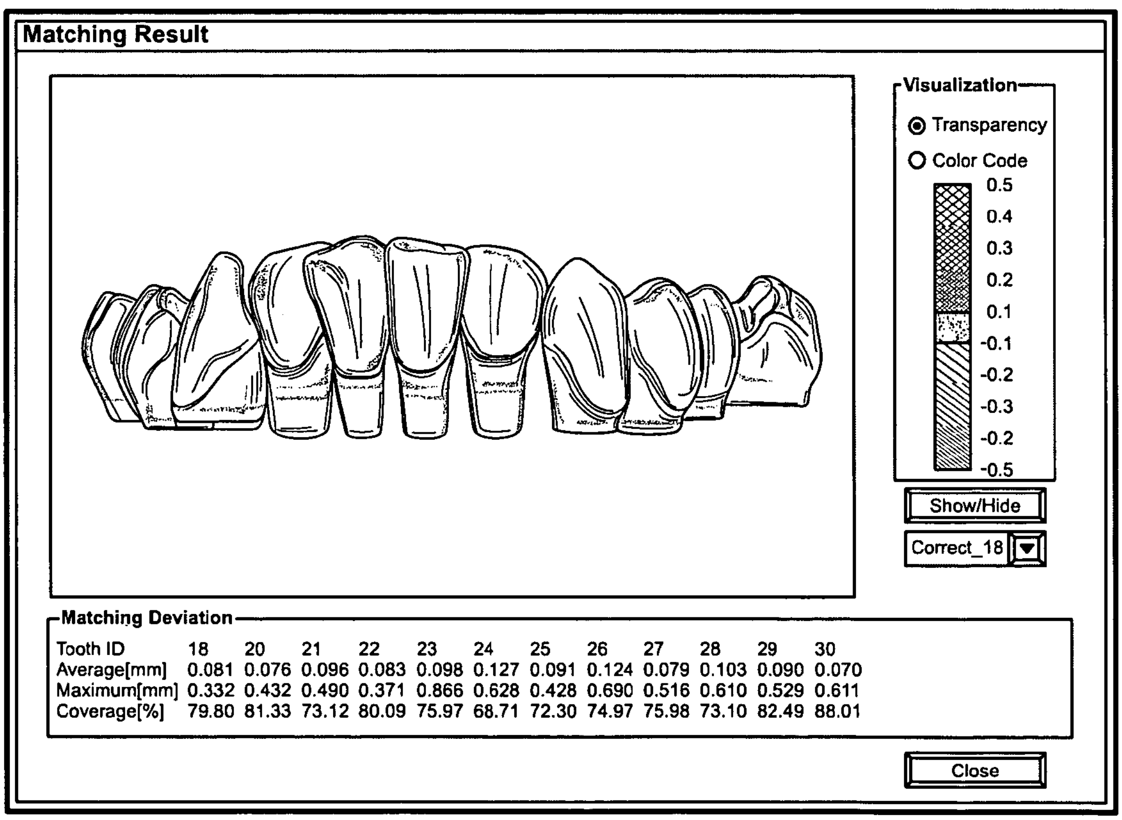

Matching Result
Visualization
Transparency
Color Code
0.5
0.4
0.3
0.2
0.1
-0.1
-0.2
-0.3
-0.2
-0.5
Show/Hide
Correct_18
Matching Deviation
Tooth ID 18 20 21 22 23 24 25 26 27 28 29 30
Average[mm] 0.081 0.076 0.096 0.083 0.098 0.127 0.091 0.124 0.079 0.103 0.090 0.070
Maximum[mm] 0.332 0.432 0.490 0.371 0.866 0.628 0.428 0.690 0.516 0.610 0.529 0.611
Coverage[%] 79.80 81.33 73.12 80.09 75.97 68.71 72.30 74.97 75.98 73.10 82.49 88.01
Close

FIG. 9B

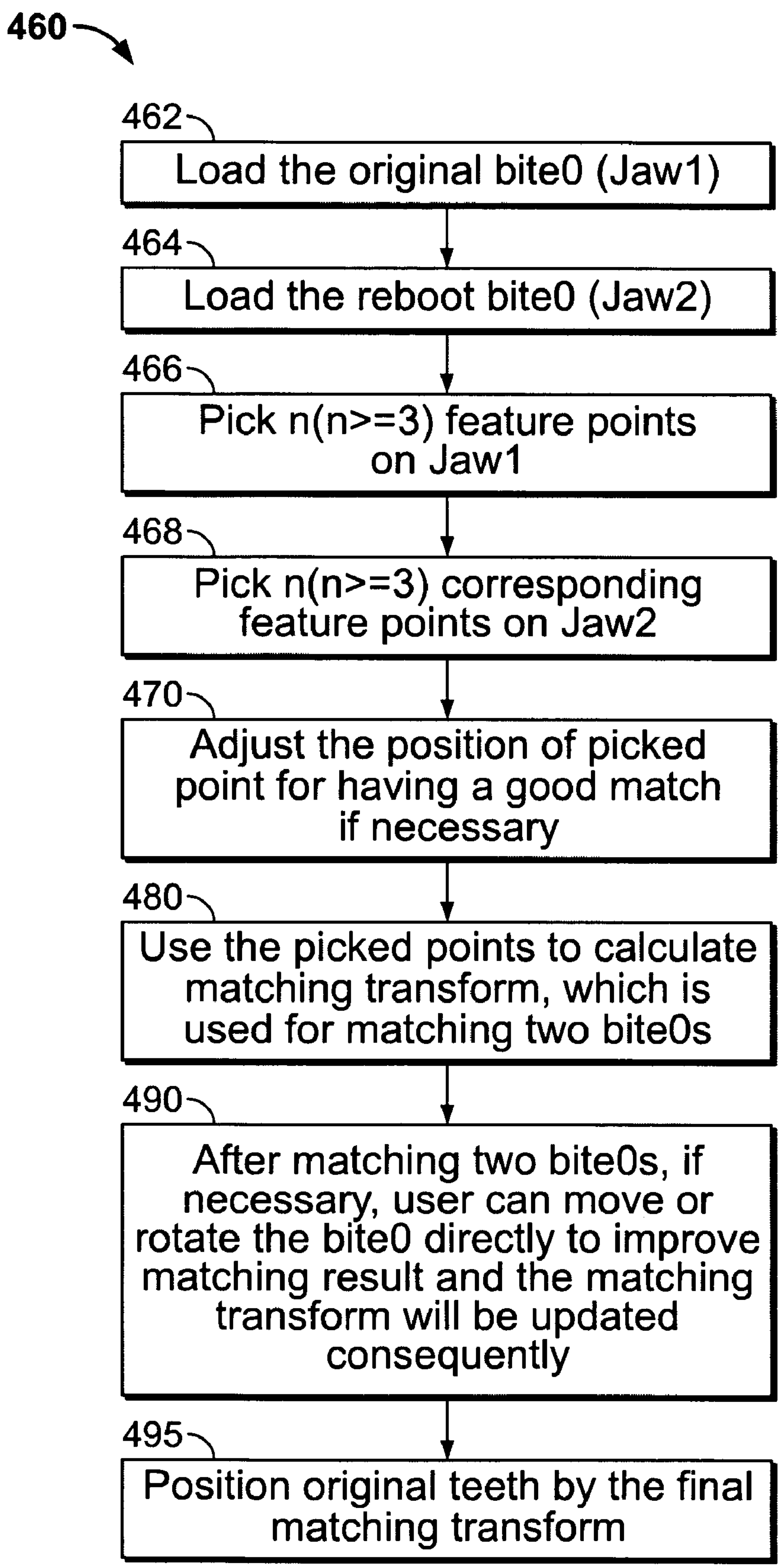

460
462
Load the original bite0 (Jaw1)
464
Load the reboot bite0 (Jaw2)
466
Pick n(n>=3) feature points on Jaw1
468
Pick n(n>=3) corresponding feature points on Jaw2
470
Adjust the position of picked point for having a good match if necessary
480
Use the picked points to calculate matching transform, which is used for matching two bite0s
490
After matching two bite0s, if necessary, user can move or rotate the bite0 directly to improve matching result and the matching transform will be updated consequently
495
Position original teeth by the final matching transform

FIG. 10A

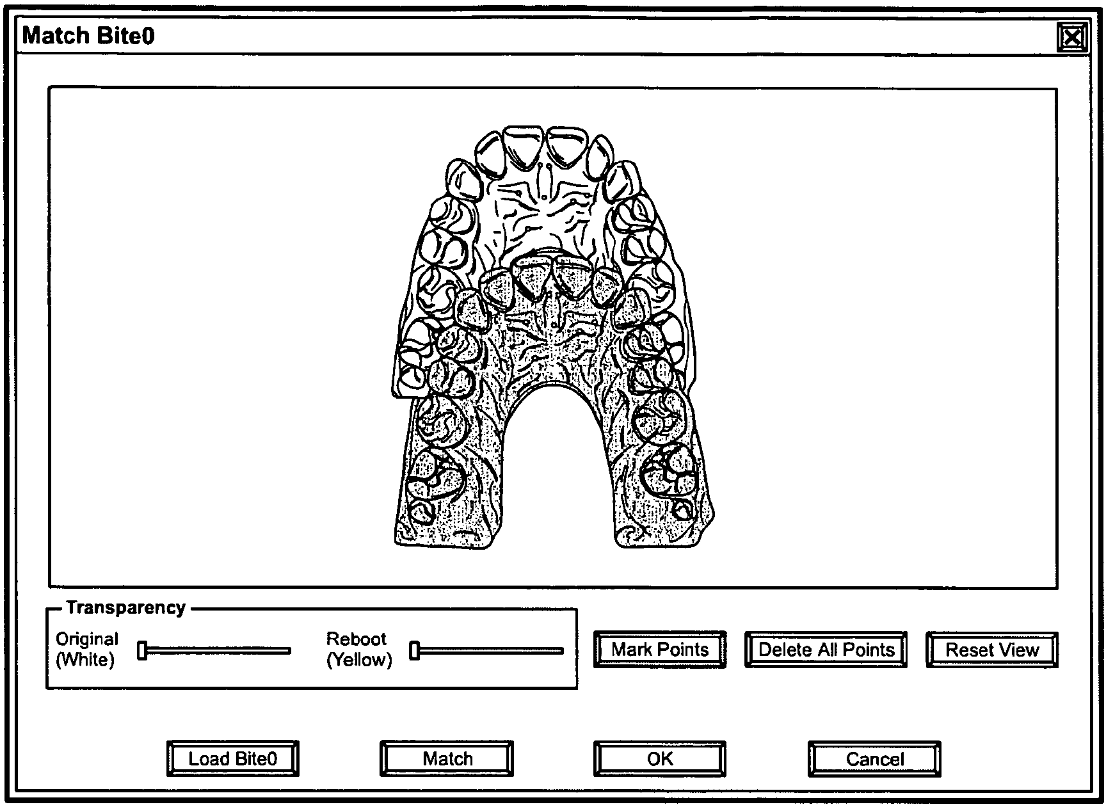


FIG. 10B

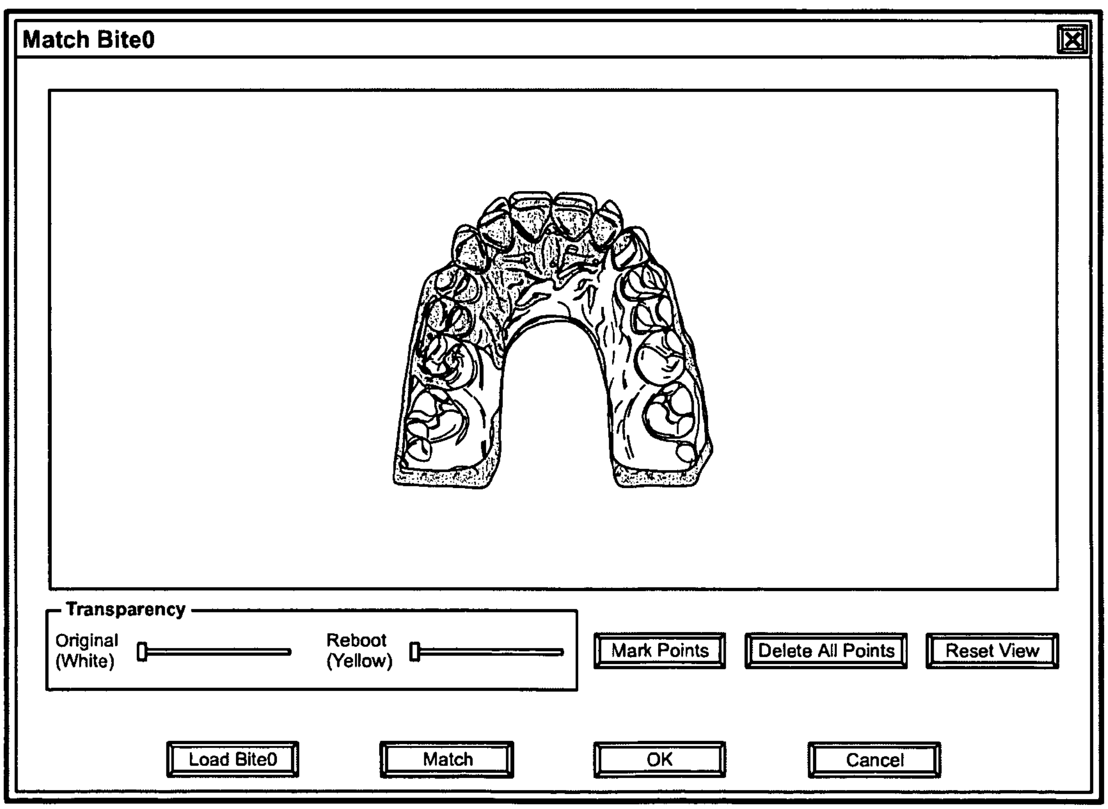


FIG. 10C

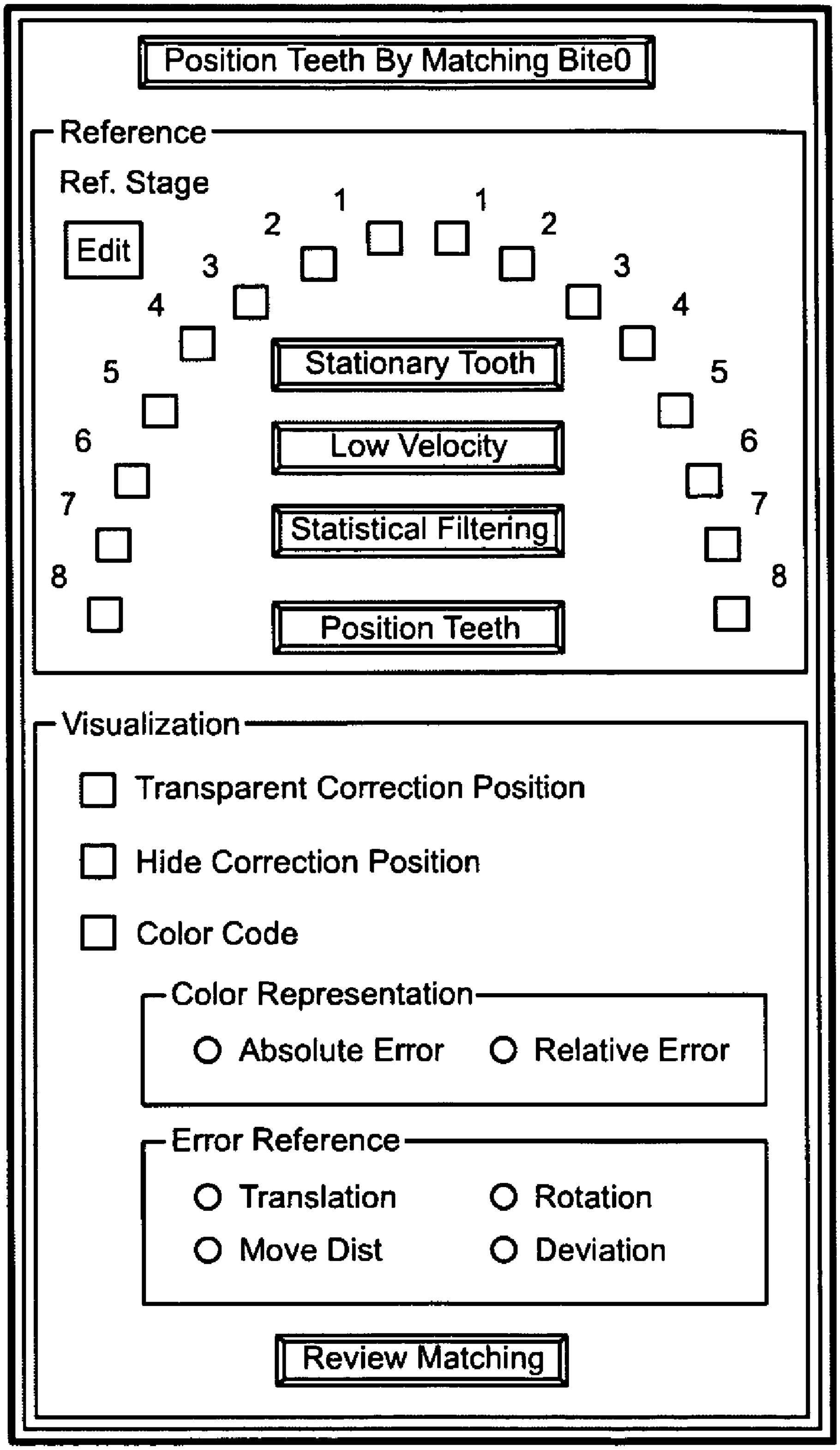
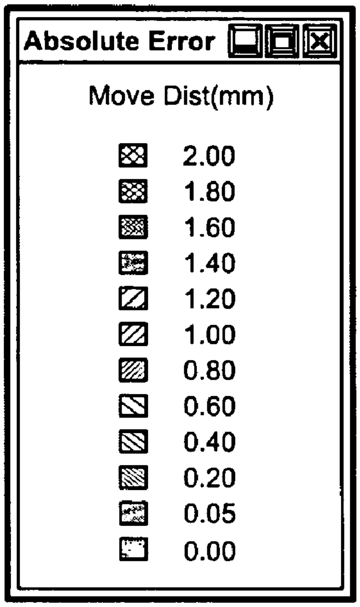
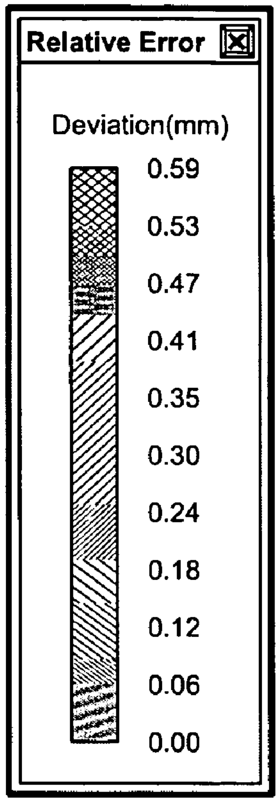

Position Teeth By Matching Bite0
Reference
Ref. Stage
Edit
1
1
2
2
3
3
4
4
5
5
6
6
7
7
8
8
Stationary Tooth
Low Velocity
Statistical Filtering
Position Teeth
Visualization
Transparent Correction Position
Hide Correction Position
Color Code
Color Representation
Absolute Error
Relative Error
Error Reference
Translation
Rotation
Move Dist
Deviation
Review Matching

FIG. 10D


Absolute Error
Move Dist(mm)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.05
0.00


Relative Error
Deviation(mm)
0.59
0.53
0.47
0.41
0.35
0.30
0.24
0.18
0.12
0.06
0.00

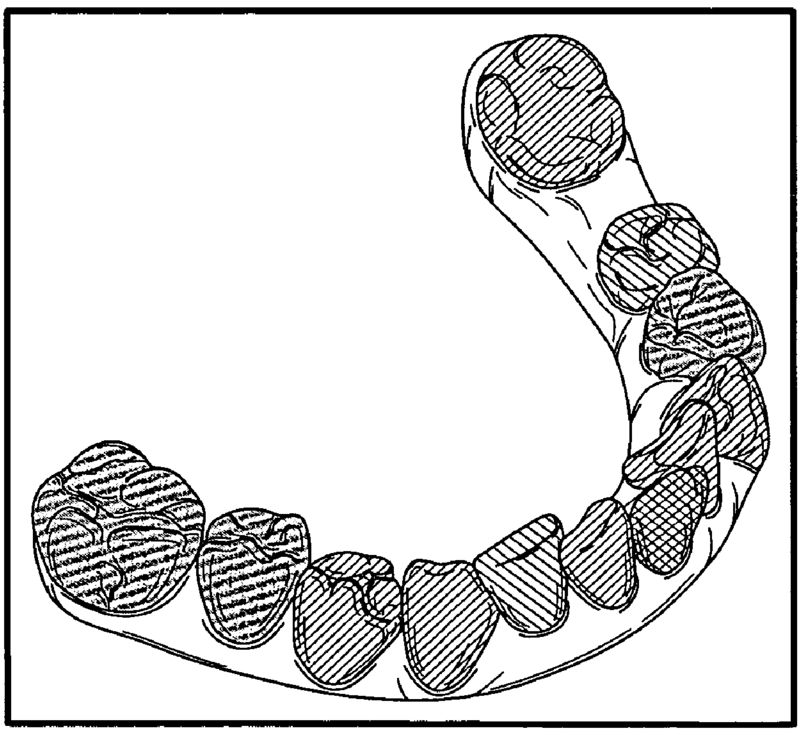


FIG. 10E

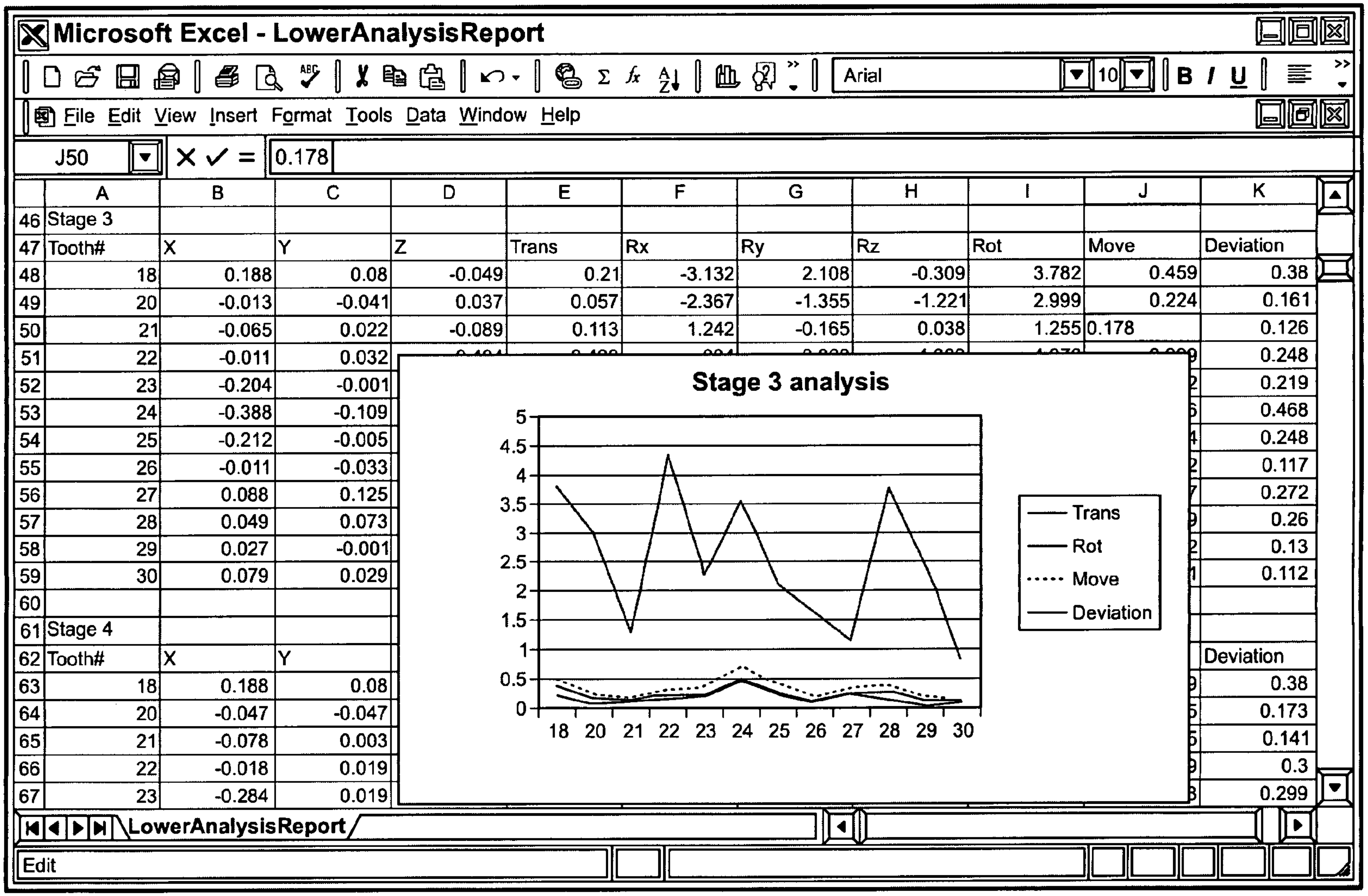

Microsoft Excel - LowerAnalysisReport
Arial 10 B I U
File Edit View Insert Format Tools Data Window Help
J50 = 0.178
A B C D E F G H I J K
46 Stage 3
47 Tooth# X Y Z Trans Rx Ry Rz Rot Move Deviation
48 18 0.188 0.08 -0.049 0.21 -3.132 2.108 -0.309 3.782 0.459 0.38
49 20 -0.013 -0.041 0.037 0.057 -2.367 -1.355 -1.221 2.999 0.224 0.161
50 21 -0.065 0.022 -0.089 0.113 1.242 -0.165 0.038 1.255 0.178 0.126
51 22 -0.011 0.032 0.248
52 23 -0.204 -0.001 0.219
53 24 -0.388 -0.109 0.468
54 25 -0.212 -0.005 0.248
55 26 -0.011 -0.033 0.117
56 27 0.088 0.125 0.272
57 28 0.049 0.073 0.26
58 29 0.027 -0.001 0.13
59 30 0.079 0.029 0.112
60
61 Stage 4
62 Tooth# X Y Deviation
63 18 0.188 0.08 0.38
64 20 -0.047 -0.047 0.173
65 21 -0.078 0.003 0.141
66 22 -0.018 0.019 0.3
67 23 -0.284 0.019 0.299
Stage 3 analysis
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
18 20 21 22 23 24 25 26 27 28 29 30
Trans
Rot
Move
Deviation
LowerAnalysisReport
Edit

FIG. 10F

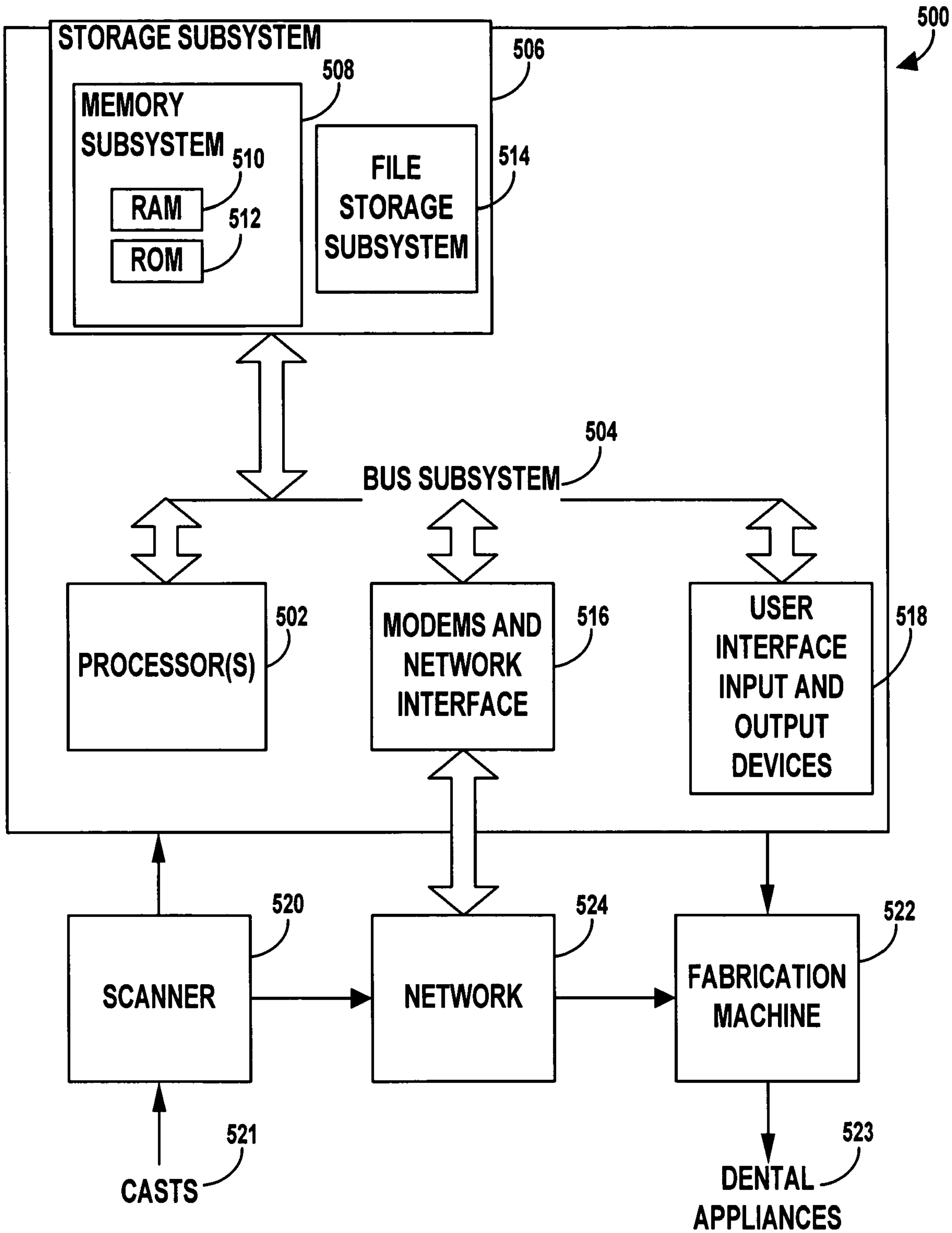

500
STORAGE SUBSYSTEM
506
MEMORY SUBSYSTEM
508
510
RAM
512
ROM
FILE STORAGE SUBSYSTEM
514
BUS SUBSYSTEM
504
PROCESSOR(S)
502
MODEMS AND NETWORK INTERFACE
516
USER INTERFACE INPUT AND OUTPUT DEVICES
518
SCANNER
520
NETWORK
524
FABRICATION MACHINE
522
CASTS
521
DENTAL APPLIANCES
523

FIG. 11

SYSTEMS AND METHODS FOR TREATMENT ANALYSIS BY TEETH MATCHING

The present invention is a continuation in part of U.S. application Ser. No. 10/225,889, filed on Aug. 22, 2002, now U.S. Pat. No. 7,077,647, and assigned to the assignee of the present invention, the content of which is hereby incorporated by reference.

BACKGROUND

The present invention is related generally to the field of orthodontics, and more particularly to systems and methods for measurement of teeth movements.

One objective in orthodontics is to move a patient's teeth to positions where the teeth function optimally and aesthetically. Conventionally, appliances such as braces are applied to the teeth of the patient by an orthodontist. Each appliance exerts continual force on the teeth and gradually urges the teeth toward their ideal positions. Over a period of time, the orthodontist adjusts the appliances to move the teeth toward their final destination.

Generally, the orthodontist specifies in a prescription the final tooth arrangement. The prescription is based on the orthodontist's knowledge and experience in selecting the intended final position of each tooth. The process of attaching the braces to teeth is tedious and painful to the patient. Additionally, each visit reduces the "chair-time" available to the orthodontist that could be used for another patient. Hence, the process of treating teeth using braces can be expensive.

Traditionally, dentists depend on manual measurement to measure dental features and orthodontic properties. They use rulers on teeth impression or X-rays images. Such manual measurements have limitations because they are manual processes and two dimensional measurements. Thus, the measurement results are not very precise and the rotation is difficult to measure. Orthodontists have also used serial head films to describe changes in tooth movement in the anterior-posterior and vertical dimensions. This technique has several limitations. These limitations include: radiation to the patient, magnification errors, operator errors, and stable and reliable anatomic reference points. Rugae change a little over the course of treatment and so indexes used for palatal matching be it drawings or solid impressions of rugae become less reliable.

SUMMARY OF THE INVENTION

The present invention includes a system, apparatus and computer-implemented method for analyzing an orthodontic treatment by using computer models of teeth.

In one aspect, a method for matching computer models of two sets of teeth includes calculating a difference for two sets of teeth shapes; finding the position of one set of teeth with respect to the other set of teeth; calculating a positional difference of the corresponding teeth; and finding a corrective path to bring one set of teeth to the other set of teeth.

Implementations of the above aspect may include one or more of the following. The calculation of a difference can include calculating and displaying shape difference for each tooth of the jaw; and identifying a corresponding location for each shape difference. Finding the position can include placing two jaw impressions in a single coordinate system; selecting a positioning reference; and determining a positional difference for each of the corresponding teeth in the

jaw impression. The method can also include matching two impressions of a jaw having teeth thereon; calculating proclination, extrusion, distalization of the teeth; and calculating rotation and orientation changes of the teeth. Moreover, the method can also include finding a correction path from current teeth positions to planned treatment teeth positions.

The advantage of the system includes one or more of the following. With the digital model, precise measurement and movement analysis can be performed. Using three-dimensional rigid body analysis accurate and complete movement of a tooth or the entire jaw can be calculated. Using the digital models, one can get a precise and complete analysis of treatment. The complete analysis can be achieved by taking two digital models, one before treatment and one after treatment, superimposing them in a virtual space, and calculating the movement of each tooth. The system provides an accurate teeth matching and jaw matching results. It reveals the shape difference between two different sets of impressions from the same teeth. It can provide a complete rigid body movement, three translations and three rotations, for each and every tooth. The system provides virtual treatment planning, which has several benefits. Using a virtual treatment plan, the clinician can evaluate treatment options in detail before beginning treatment. It can also serve as a constant objective reference during office visits so that planned treatment goals can be kept visible. The virtual treatment model can also serve as a motivating tool. The clinician can show the virtual model to the patient during office visits to allow the patient to continually see where the treatment is ultimately going.

The system allows the creation of accurate tooth geometry and a gingival model from scanned geometry. It provides feedback and interactivity to a user during the model creation and virtual treatment planning, which can allow the user to make informed decisions about the treatment plan in the process of creating it. Having the ability to simply and reliably compare treatment outcomes to treatment plans can allow the detailed study of many cases.

For treatment outcome analysis, good matching to the surfaces in the rugae area rather than relying on user selections could possibly allow more accurate and repeatable measurements to be made. Using other non-tooth areas in the mouth such as parts of the gingiva surface which tend not to change as teeth move (e.g. surfaces further away from the gingival line) could allow better analysis of the lower jaw as well. Using 3D scans of the patient that included other skeletal structures in the head could provide the best reference for measurements.

Performing analyses during treatment is valuable. It allows adjustments to be made to a treatment in progress should it go off course from the original intended plan. The difference between the planned and actual positions of the teeth could be computed to determine the deviation from the plan. This difference can then be used to adjust the plan for the remainder of the treatment. A set of appliances can then be made to correct the deviation and finish executing the treatment plan. Finally, consistently performing these analyses during treatments can provide a useful database that could be used to study treatment progress over time.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an elevational diagram showing the anatomical relationship of the jaws of a patient.

FIG. 2A illustrates in more detail the patient's lower jaw and provides a general indication of how teeth may be moved by the methods and apparatus of the present invention.

FIG. 2B illustrates a single tooth from FIG. 2A and defines how tooth movement distance is determined.

FIG. 2C illustrates the jaw of FIG. 2A together with an incremental position adjustment appliance.

FIG. 3 shows an exemplary bite set process.

FIG. 4 shows an exemplary process for matching of original teeth data with current teeth data.

FIG. 5 shows a process for positioning of a newly scanned jaw in the original coordinate system

FIG. 6 shows an exemplary report analysis generation process.

FIG. 7 shows an exemplary process to create reboot appliances in case the patient's teeth are out of synchronization with the treatment plan.

FIG. 8 shows an exemplary functional summary process.

FIGS. 9A and 9B illustrate exemplary shape differences between two corresponding teeth.

FIG. 10A shows an exemplary embodiment for matching shapes based on rugae.

FIGS. 10B–10F show exemplary user interfaces.

FIG. 11 is a block diagram illustrating a system for generating appliances in accordance with the present invention.

DESCRIPTION

FIG. 1 shows a skull **10** with an upper jaw bone **22** and a lower jaw bone **20**. The lower jaw bone **20** hinges at a joint **30** to the skull **10**. The joint **30** is called a temporal mandibular joint (TMJ). The upper jaw bone **22** is associated with an upper jaw **101**, while the lower jaw bone **20** is associated with a lower jaw **100**. A computer model of the jaws **100** and **101** is generated, and a computer simulation models interactions among the teeth on the jaws **100** and **101**. The computer simulation allows the system to focus on motions involving contacts between teeth mounted on the jaws. The computer simulation allows the system to render realistic jaw movements that are physically correct when the jaws **100** and **101** contact each other. The model of the jaw places the individual teeth in a treated position. Further, the model can be used to simulate jaw movements including protrusive motions, lateral motions, and "tooth guided" motions where the path of the lower jaw **100** is guided by teeth contacts rather than by anatomical limits of the jaws **100** and **101**. Motions are applied to one jaw, but may also be applied to both jaws. Based on the occlusion determination, the final position of the teeth can be ascertained.

Referring now to FIG. 2A, the lower jaw **100** includes a plurality of teeth **102**, for example. At least some of these teeth may be moved from an initial tooth arrangement to a final tooth arrangement. As a frame of reference describing how a tooth may be moved, an arbitrary centerline (CL) may be drawn through the tooth **102**. With reference to this centerline (CL), each tooth may-be moved in orthogonal directions represented by axes **104**, **106**, and **108** (where **104** is the centerline). The centerline may be rotated about the axis **108** (root angulation) and the axis **104** (torque) as indicated by arrows **110** and **112**, respectively. Additionally, the tooth may be rotated about the centerline, as represented by an arrow **112**. Thus, all possible free-form motions of the tooth can be performed.

FIG. 2B shows how the magnitude of any tooth movement may be defined in terms of a maximum linear translation of any point P on a tooth **102**. Each point P**1** will undergo a cumulative translation as that tooth is moved in any of the orthogonal or rotational directions defined in FIG. 2A. That is, while the point will usually follow a nonlinear path, there is a linear distance between any point in the tooth when determined at any two times during the treatment. Thus, an arbitrary point P**1** may in fact undergo a true side-to-side translation as indicated by arrow d**1**, while a second arbitration point P**2** may travel along an arcuate path, resulting in a final translation d**2**. Many aspects of the present invention are defined in terms of the maximum permissible movement of a point P**1** induced on any particular tooth. Such maximum tooth movement, in turn, is defined as the maximum linear translation of that point P**1** on the tooth that undergoes the maximum movement for that tooth in any treatment step.

FIG. 2C shows one adjustment appliance **111** which is worn by the patient in order to achieve an incremental repositioning of individual teeth in the jaw as described generally above. The appliance is a polymeric shell having a teeth-receiving cavity. This is described in U.S. application Ser. No. 09/169,036, filed Oct. 8, 1998, now U.S. Pat. No. 6,450,807, which claims priority from U.S. application Ser. No. 08/947,080, filed Oct. 8, 1997, now U.S. Pat. No. 5,975,893, which in turn claims priority from provisional application number 60/050,352, filed Jun. 20, 1997 (collectively the "prior applications"), the full disclosures of which are incorporated by reference.

As set forth in the prior applications, each polymeric shell may be configured so that its tooth-receiving cavity has a geometry corresponding to an intermediate or final tooth arrangement intended for the appliance. The patient's teeth are repositioned from their initial tooth arrangement to a final tooth arrangement by placing a series of incremental position adjustment appliances over the patient's teeth. The adjustment appliances are generated at the beginning of the treatment, and the patient wears each appliance until the pressure of each appliance on the teeth can no longer be felt. At that point, the patient replaces the current adjustment appliance with the next adjustment appliance in the series until no more appliances remain. Conveniently, the appliances are generally not affixed to the teeth and the patient may place and replace the appliances at any time during the procedure. The final appliance or several appliances in the series may have a geometry or geometries selected to overcorrect the tooth arrangement, i.e., have a geometry which would (if fully achieved) move individual teeth beyond the tooth arrangement which has been selected as the "final." Such over-correction may be desirable in order to offset potential relapse after the repositioning method has been terminated, i.e., to permit movement of individual teeth back toward their pre-corrected positions. Over-correction may also be beneficial to speed the rate of correction, i.e., by having an appliance with a geometry that is positioned beyond a desired intermediate or final position, the individual teeth will be shifted toward the position at a greater rate. In such cases, the use of an appliance can be terminated before the teeth reach the positions defined by the appliance.

The polymeric shell **111** can fit over all teeth present in the upper or lower jaw. Often, only certain one(s) of the teeth will be repositioned while others of the teeth will provide a base or an anchor region for holding the appliance **111** in place as the appliance **111** applies a resilient repositioning force against the tooth or teeth to be repositioned. In complex cases, however, multiple teeth may be repositioned at some point during the treatment. In such cases, the moved teeth can also serve as a base or anchor region for holding the repositioning appliance.

The polymeric appliance **111** of FIG. **2**C may be formed from a thin sheet of a suitable elastomeric polymer, such as Tru-Tain 0.03 in, thermal forming dental material, available from Tru-Tain Plastics, Rochester, Minn. Usually, no wires or other means will be provided for holding the appliance in place over the teeth. In some cases, however, it will be desirable or necessary to provide individual anchors on teeth with corresponding receptacles or apertures in the appliance **111** so that the appliance can apply an upward force on the tooth that would not be possible in the absence of such an anchor.

FIG. **3** shows an exemplary Treatment Outcome Analysis by Teeth Matching process **200**. The process initially creates dental models from the impression and assigns an appropriate coordinate system. Two models are scanned and segmented to create virtual models as described above. Then, a body coordinate system for each tooth is established. The motion of the body coordinate system is used to express the movement of the teeth in a simple way. Next, the process sets a common coordinate system for teeth in the two impressions. This is an important process in the comparison of two models. The impressions are slightly different each time they are taken, and the geometry of a tooth in each impression is also slightly different. In order to compare the movement of teeth in two different impressions, the coordinate system for each tooth must be consistent between the impressions. In order to establish a common coordinate system, the software performs tooth-to-tooth geometric matching. This also determines the relative coordinate transform between the two teeth. In general, given two sets of geometry D**1** and D**2** (geometry of teeth) they determine the 3D transformation T that will align them. Often the process is called geometry registration. The registration process is accomplished by determining a transformation T that minimizes the discrepancy between D**1** and D**2**. In this work, the discrepancy is defined as the square sum of normal distance between a vertex on D**1** and a surface on D**2**. An iterative optimization method is employed to refine the solution until a best fit match is found.

Once the teeth are aligned, all comparisons are done using the coordinate system of D**1**. Since the geometry of the teeth may not be exactly the same due to the interproximal modeling and the addition of approximate root geometry, this algorithm only uses surfaces that were present in the original scan data for matching. This data is recorded for each scanned model, and retained as the model is segmented. This process allows the geometry of the original and the new impression to be matched. Differences between the two scans can be due to the quality of the impression or scanning process, or actual wear on the patient's teeth.

The process then establishes a reference frame for measurement. Now that it is possible to determine the relative position of corresponding teeth, it is necessary to establish a frame of reference from which to interpret this relative transform. Having the correct reference frame means that if the two teeth D**1** and D**2** are in the same position in both models, then T is the identity transform. Once this reference frame is found, the difference in tooth position can be described in relative or absolute terms. To find the absolute movement of the teeth, an external reference frame must be incorporated. Otherwise, only a relative movement of teeth can be calculated.

Once the relative position of the impressions is determined, the movement of each tooth is described as a rigid body transformation. The rigid body transformation is broken down into clinically meaningful directions: distal-mesial, buccal-lingual, and intrusive-extrusive directions. The discrepancy between the surfaces of corresponding teeth can also describe the amount of movement of each tooth.

Referring now to FIG. **3**, an original treatment case is loaded (**202**). Next, a current jaw impression is loaded (**204**). The teeth data from the original treatment case is compared against the teeth data from the current jaw impression (**206**). Next, the new jaw data is positioned in the original coordinate system (**208**). The process **200** then compares the original jaw data against the new jaw data (**210**). Based on the comparison, the Process **200** generates an analysis report (**220**). Alternatively, it can create a mid-course correction data file (MCC ADF) (**230**). In yet another option, the process **200** can generate a visualization showing the discrepancy (**240**).

The process **206** of FIG. **3** matches data using a tooth by tooth approach. By matching tooth by tooth, the process determines the difference between tooth geometry in two different impressions. Even though the same tooth is scanned, there may be slight differences between impressions. This process reveals the difference between two different impressions.

The process also determines necessary coordinate transformations from the expected 3D coordinates for each tooth to the 3D coordinates for the corresponding tooth in the impression. Once this process is done, the difference of the impression of the individual tooth is ascertained. Based on the information, the process determines tooth alignment data in the current position.

In the next process **208**, a second matching operation is performed to determine the position of the new jaw relative to the original coordinate system The current teeth alignment data previously determined is then compared against the current stage. This process positions the scanned jaw impression relative to the original jaw position. Once each tooth is placed, the process can determine the individual difference between the current jaw and original jaw. The process then provides three options: visualize any discrepancy; report the discrepancy in a report or a failure analysis; and create MCC ADF (the file that moves the tooth from its current tooth impression to the expected tooth location).

For example, in one embodiment for visualizing differences between a virtual treatment plan and a scan taken later during treatment, teeth are colored according to a scale to indicate that the tooth is in a different position or orientation in the new scan. Since the tooth movement is represented simply by the movement of the tooth's coordinate system, a comprehensive analysis of the movement can be easily obtained by examining the difference in the coordinate systems of corresponding teeth. The software can display these differences along a variety of dimensions: translation, rotation, surface deviation, and the tooth movement speed metric.

Referring now to FIG. **4**, the matching of the original teeth data with the current teeth data of box **206** is detailed. In FIG. **4**, the process approximates the current positioning of the current teeth (**300**). Next, the process (**304**) is iterated for each tooth in **302**. The process **304** creates sample points Pi on the current tooth crown surface (**306**). Next, it finds the corresponding closest point Qi of each Pi on the original tooth crown surface (**308**). The process then calculates an error of value in this case, the error value is computed as the sum of the distance between Pi and Qi, (**310**). The process then computes a rigid transformation between two teeth that minimizes the error (**312**). The current tooth is then repositioned with the transform (**314**). The process of FIG. **4** is repeated until an error value is less than a predetermined termination criterion or the number of iterations exceeds a predetermined value (**316**). Finally, the process provides a visual report of the deviation (**318**).

The process of FIG. **4** positions the current teeth with respect to original teeth using an approximate position. In one embodiment, the process positions two teeth approximately based on each crown center and tooth local coordinate system. Then, for each tooth, a matching operation is performed. The matching operation is an iteration process that minimizes an error value while trying to find the appropriate tooth location. The process finds points on the original tooth crown and finds corresponding points on the current tooth. The process finds each Pi on the current tooth and Qi of the original tooth and calculates the distance between Pi and Qi. The process determines a transformation that minimizes the square sum of these errors. Then the process positions the teeth and starts again. A new point Pi and a new point Qi are selected, and the process finds the difference and determines the transformation that minimizes the error. The above steps are iterated until the error is less than termination criteria or a maximum number of iterations is reached. Then the process graphically illustrates the difference.

Turning now to FIG. **5**, the positioning of the new jaw in the original coordinate system (**208**) is detailed. First, the process receives a positioning option from a user (**319**). If the user specifies stationary teeth option (**320**), the process uses stationary teeth as a set of reference teeth (**322**). Alternatively, if the users specify a low velocity model (**330**), the process uses low velocity teeth as reference teeth (**332**). From the positioning option **319**, if the users specify statistical filtering (**340**) the process uses teeth with small standard error as reference teeth (**342**).

From boxes **322**,**332**, or **342**, the process generates various sample points on the reference teeth and corresponding points on the current teeth (**344**). Next, it calculates position transformation using the sample points (**346**). It processes and positions the current teeth with the transformation (**348**) and generates a visualization of the difference (**350**.)

The process provides three different options to position the new jaw in the original coordinate system. User can choose one of the options freely. The first option relies on stationary teeth that are expected to remain stationary throughout the stages. The stationary teeth are then used as a landmark for comparison purposes. Low velocity option allows the user to pick a tooth that moves at a relatively low velocity as a landmark approximation. The statistical filtering approach can be used for selecting small standard error as reference teeth.

Turning now to FIG. **6**, the report analysis generation process **220** is detailed. For each individual tooth, the report generates discrepancy information in terms of translation, rotation, movement distance and deviation, and an average for all of the teeth. First, the teeth are positioned (**221**). Next, the process obtains a first transform for an original position and a second transform for the current position (**352**). From **352**, the process calculates the translation (**354**) and proceeds to determine the average, maximum and minimum of the translations (**356**). Alternatively, the process **220** can also calculate rotation for Rx, Ry, Rz (**358**) and again determines the average, maximum and minimum (**360**). From **352**, the process can also calculate move distance of a tooth (**362**) and generates a report of the average, maximum, and minimum (**364**). Additionally, the process **220** can also calculate the deviation (**366**) and generate a report with the average, maximum and minimum (**368**). From **356**, **360**, **364**, and **368**, the process **220** can generate an export to a text file (TXT) (**370**) or to a comma separated file (CSV) for the user to perform subsequent analysis (**372**).

Turning now to FIG. **7**, a mid-course correction data file (MCC ADF) create operation **230** is detailed. For treatment plans whose teeth movements have deviated from the treatment plan, the process generates files to bring the treatment back on track.

First, the process obtains the deviation stage and a target stage (**380**). Next, the process sets the position at a deviation stage as the initial position (**382**). Additionally, the process sets a position at a target stage as the final position (**384**). Finally, the process creates a new ADF using the initial position and the final position (**386**). The process obtains the deviation stage, or the stage where the current impression is taken and where the patient's teeth have gone off the planned path so the aligner fails to fit the teeth. The system also obtains the target stage, which is the stage that the patient's teeth is expected to be. The process uses the current teeth position as the initial position and the target stage of the original treatment plan as the final position.

Referring now to FIG. **8**, a functional summary process **400** is shown. First, treatment outcome analysis is performed (**402**). From the treatment outcome analysis, the process **400** performs four operations in sequence. The first operation is to match the treatment with a correction ADF (**404**). In this operation, the tooth is matched tooth by tooth (**406**) deviations are quantified (**408**). The deviation is visualized, for example using color code or transparency values, among others (**410**). In a second operation where the teeth are positioned (**412**), the operation includes specifying a reference stage (**414**), manually selecting a set of reference teeth (**416**), automatically selecting a set of reference teeth (**418**), specifying an error reference (**420**), specifying color representation (**422**) and visualizing the discrepancy (**424**).

In the third operation, analysis of the match result is performed (**426**). First, the position discrepancy is computed (**428**). Next, a text file is generated (**430**) or alternatively, a CSV file can be generated (**432**).

In the final operation, the process **400** creates the MCC ADF (**440**). In this operation, the target stage can be specified (**442**) and the result in the MCC file is exported for correction treatment (**444**).

The above described system matches two different impressions of a patient, one before treatment and one after treatment, the method positions them together in a single three-dimensional space, and calculates the individual tooth movement. This also includes finding the intermediate treatment if the patient's current teeth are off from the intended treatment course.

In this system, there are two different sets of digital models of teeth, the original teeth and the new teeth. First, a comparison of two corresponding teeth in the different set is found by an iterative searching algorithm. The search algorithm finds the relative position of the teeth by minimizing the distance between two superimposed teeth. The matching process is completed throughout the entire teeth of a jaw. After matching the teeth, the shape difference between each of the corresponding teeth, one before treatment and one after treatment, can be identified as a by-product of the matching. This teeth matching provides a foundation for jaw matching so that each new tooth position can be represented relative to the original tooth position. Then, the matched position of individual teeth is used to position the entire jaw. The entire jaw needs an external reference to set the position. A fixed external reference such as rugae in the patient's mouth can be used. If a fixed external reference is not available, some teeth can be used for the reference as well. Once the entire jaw is positioned, the relative movement or discrepancy is precisely calculated. The calculated results are reported in text and also visualized on computer screen.

FIGS. **9**A and **9**B illustrate that the shape difference of two corresponding teeth can be the average deviation, maximum deviation, or coverage percentage, among others. The deviation is defined as the distance between the sampled point on one tooth and its projection point on the other tooth. For displaying the difference in teeth position variance, a color-coded model and a transparent tooth model are used in these exemplary figures.

FIG. **10**A shows an exemplary embodiment for matching shapes based on rugae. For matching rugae, the user locates points on the new model, and picks points on the treatment plan model that correspond to those points. These points are then matched such that the models are positioned so they closely align in the regions around the points (i.e. the rugae region), by applying a transform T_{ref} to one of the models. After this reference frame is established, the actual relative transform between teeth can be calculated simply by $T \cdot T_{ref}^{-1}$.

If the rugae region is not available, stationary or slow-moving teeth can be used to establish a reference. For example, if anterior teeth are expected to move, then molars can be used as the reference. Relative movement between the corresponding teeth is then measured compared to the reference teeth. The disadvantage to this technique is that it is limited to relative movements and does not take into account forces that may be moving the reference teeth.

Turning now to FIG. **10**A, the process loads the original impression of the teeth or bite**0** (Jaw**1**) (**462**). Next, the process loads the reboot impression of the teeth (Jaw**2**) **464**. The process selects a plurality of points (for example more than three) feature points on Jaw**1** (**466**) and corresponding feature points on Jaw**2** (**468**). The process then allows the user to adjust the position of picked point for having a good match, if necessary (**470**). In one embodiment, the user can match the jaws by the marked points on the captured jaw models. If the user wants to modify the position of the marking point, user can move the point by selecting the point and then dragging the point to the desired position. Also, user can delete a point by right clicking the point and then selecting “delete” from the right-click menu.

The process then uses the picked points to calculate a matching transform, which is used for matching two scanned jaw models (**480**). After matching two scanned jaw models, if necessary, user can move or rotate the jaw model directly to improve matching result and the matching transform will be updated consequently (**490**). The process then positions the original teeth by the final matching transform **495**.

If the rugae region is not available, stationary or slow-moving teeth can be used to establish a reference. For example, if anterior teeth are expected to move, then molars can be used as the reference. Relative movement between the corresponding teeth is then measured compared to the reference teeth. The disadvantage to this technique is that it is limited to relative movements and does not take into account forces that may be moving the reference teeth.

The process of FIG. **10**A allows a new scan of a mid-course correction (MCC) case to be best fitted to the original approved treatment. A best-fit comparison of the overlapped models would then allow tooth positions to be analyzed for discrepancies between treatments. The process can be used for positioning the correction teeth together with the original teeth based on the reference stage and reference teeth. The reference teeth can be specified manually or automatically. The discrepancies between the original teeth/position and correction teeth/position can be quantified and visualized. The information in analysis report is focused on the position discrepancies between the original treatment and the new impression. The report is helpful for users to study MCC cases. Based on teeth matching, positioning teeth by matching original bite**0** and reboot bite**0**, or by specified reference stage and teeth, and target stage, MCC ADF can be created. The process can be used to place the treatment back on track without having to completely redo the case. This will get the original treatment away from the deviation without having to waste any materials, and the treatment will be able to use most of the original aligners sent to the doctor, using the additional ones generated to correct the deviation.

FIGS. **10**B–**10**F show exemplary user interfaces. In FIG. **10**B, two impression models (bite**0**s) are loaded into a window. For matching two bite**0**s, user can match them by marked points on the bite**0**s. In this embodiment, the user can mark the points on the bite**0**s. The two groups of points on the bite**0**s are related by the marking sequence. Besides matching bite**0**s by marking points, user can manually match them by moving/rotating them.

FIG. **10**C shows an exemplary user interface after matching the two bite**0**s. The original teeth will be positioned at a new position based on the bite**0** matching. With a transparency slider, the user can make the bite**0** transparent so that is helpful for user to observe the matching result. By clicking a Reset View button, user can move the objects' center to the center of the view.

FIG. **10**D shows an exemplary user interface where the user can match the bite**0**s using the Input Reference Stage user interface. There are four approaches for a user to choose reference teeth. If the user wants to select a stationary tooth/teeth as a reference, the user should click the Stationary Tooth button. If the user wants to select a low velocity tooth/teeth as a reference, the user should click the Low Velocity button. If the user wants to use a statistical filtering approach to choose referenced teeth, the user should click the Statistical Filtering button. The user can also choose the teeth by simply clicking the check boxes for the corresponding teeth. After choosing the reference stage and reference teeth, the user can position teeth by clicking the Position Teeth button.

FIG. **10**E shows an exemplary illustration of mismatches in the bite**0**s. In order to visualize the discrepancies between the original position and correction position, the user can check Transparent Correction Position, Hide Correction Position or Color Code. For color code, two color representations are provided: Absolute Error and Relative Error as shown in FIG. **10**E. For error reference, the user can choose Translation, Rotation, Move Distance or Deviation as reference. In one embodiment, modeless dialog boxes are used for explaining the meaning of different colors. For example, in FIG. **10**E, the left dialog is for absolute error color code, and the right one is for relative error color code.

The resulting variances can be exported as text or spreadsheet data for analysis. FIG. **10**F shows an exemplary data analysis of teeth positional variances using a spreadsheet analysis.

The system thus provides a 3-dimensional superimposition tool that measures dental changes based on an algorithm of best fit. The software consists of matching the teeth and common coordinates to create the measurements. The teeth matching works by comparing the anatomy of the teeth from the two time points and finds the best fit between them. The software then uses selected internal reference points such as stable teeth to establish a relative position. Stable structures such as the palatal rugae can be used as stable external reference points. After the software superimposes the two images, displacements are measured. Each individual tooth movement can be described by six different measurements (tip, torque, rotation, etc).

This tool allows the opportunity to select which teeth will serve as stable structures to be used for superimposition. The superimposition is done 3-dimensionally and therefore the results can be viewed in the three planes. In addition to superimposing two models—at two time points, this software can also be used to superimpose an existing model with that of any stage of the virtual treatment. This can be used to evaluate how well treatment is progressing according to the projected virtual treatment plan.

FIG. **11** is a simplified block diagram of a data processing system **500**. Data processing system **500** typically includes at least one processor **502** that communicates with a number of peripheral devices over bus subsystem **504**. These peripheral devices typically include a storage subsystem **506** (memory subsystem **508** and file storage subsystem **514**), a set of user interface input and output devices **518**, and an interface to outside networks **516**, including the public switched telephone network. This interface is shown schematically as "Modems and Network Interface" block **516**, and is coupled to corresponding interface devices in other data processing systems over communication network interface **524**. Data processing system **500** may include a terminal or a low-end personal computer or a high-end personal computer, workstation or mainframe. The user interface input devices typically include a keyboard and may further include a pointing device and a scanner. The pointing device may be an indirect pointing device such as a mouse, trackball, touchpad, or graphics tablet, or a direct pointing device such as a touchscreen incorporated into the display. Other types of user interface input devices, such as voice recognition systems, may be used. User interface output devices may include a printer and a display subsystem, which includes a display controller and a display device coupled to the controller. The display device may be a cathode ray tube (CRT), a flat-panel device such as a liquid crystal display (LCD), or a projection device. The display subsystem may also provide nonvisual display such as audio output. Storage subsystem **506** maintains the basic programming and data constructs that provide the functionality of the present invention. The software modules discussed above are typically stored in storage subsystem **506**. Storage subsystem **506** typically comprises memory subsystem **508** and file storage subsystem **514**. Memory subsystem **508** typically includes a number of memories including a main random access memory (RAM) **510** for storage of instructions and data during program execution and a read only memory (ROM) **512** in which fixed instructions are stored. In the case of Macintosh-compatible personal computers the ROM would include portions of the operating system; in the case of IBM-compatible personal computers, this would include the BIOS (basic input/output system). File storage subsystem **514** provides persistent (nonvolatile) storage for program and data files, and typically includes at least one hard disk drive and at least one floppy disk drive (with associated removable media). There may also be other devices such as a CD-ROM drive and optical drives (all with their associated removable media). Additionally, the system may include drives of the type with removable media cartridges. The removable media cartridges may, for example be hard disk cartridges, such as those marketed by Syquest and others, and flexible disk cartridges, such as those marketed by Iomega. One or more of the drives may be located at a remote location, such as in a server on a local area network or at a site on the Internet's World Wide Web. In this context, the term "bus subsystem" is used generically so as to include any mechanism for letting the various components and subsystems communicate with each other as intended. With the exception of the input devices and the display, the other components need not be at the same physical location. Thus, for example, portions of the file storage system could be connected over various local-area or wide-area network media, including telephone lines. Similarly, the input devices and display need not be at the same location as the processor, although it is anticipated that the present invention will most often be implemented in the context of PCS and workstations. Bus subsystem **504** is shown schematically as a single bus, but a typical system has a number of buses such as a local bus and one or more expansion buses (e.g., ADB, SCSI, ISA, EISA, MCA, NuBus, or PCI), as well as serial and parallel ports. Network connections are usually established through a device such as a network adapter on one of these expansion buses or a modem on a serial port. The client computer may be a desktop system or a portable system. Scanner **520** is responsible for scanning casts of the patient's teeth obtained either from the patient or from an orthodontist and providing the scanned digital data set information to data processing system **500** for further processing. In a distributed environment, scanner **520** may be located at a remote location and communicate scanned digital data set information to data processing system **500** over network interface **524**. Fabrication machine **522** fabricates dental appliances based on intermediate and final data set information received from data processing system **500**. In a distributed environment, fabrication machine **522** may be located at a remote location and receive data set information from data processing system **500** over network interface **524**.

Various alternatives, modifications, and equivalents may be used in lieu of the above components. Although the final position of the teeth may be determined using computer-aided techniques, a user may move the teeth into their final positions by independently manipulating one or more teeth while satisfying the constraints of the prescription. Additionally, the techniques described here may be implemented in hardware or software, or a combination of the two. The techniques may be implemented in computer programs executing on programmable computers that each includes a processor, a storage medium readable by the processor (including volatile and nonvolatile memory and/or storage elements), and suitable input and output devices. Program code is applied to data entered using an input device to perform the functions described and to generate output information. The output information is applied to one or more output devices. Each program can be implemented in a high level procedural or object-oriented programming language to operate in conjunction with a computer system. However, the programs can be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language. Each such computer program can be stored on a storage medium or device (e.g., CD-ROM, hard disk or magnetic diskette) that is readable by a general or special purpose programmable computer for configuring and operating the computer when the storage medium or device is read by the computer to perform the procedures described. The system also may be implemented as a computer-readable storage medium, configured with a computer program, where the storage medium so configured causes a computer to operate in a specific and predefined manner. Further, while the invention has been shown and described with reference to an embodiment thereof, those skilled in the art will understand that the above and other changes in form and detail may be made without departing from the spirit and scope of the following claims.

What is claimed is:

1. A method for matching computer models of a jaw, the method comprising:

loading a first computer model of a jaw having teeth in initial positions;

loading a second computer model of the jaw, wherein positions of at least some of the teeth in the second computer model are different than the initial positions;

identifying at least one reference point on a region of the first computer model, the region comprising a portion of the jaw other than the teeth;

identifying a corresponding reference point on a corresponding region of the second computer model for each point identified on the first model;

matching the region of the first computer model with the corresponding region of the second computer model, using the identified reference points;

matching the first and second computer models as a whole, using the matched regions; and

calculating positional differences between the teeth in their initial positions and the teeth in their positions in the second computer model, using the matched regions as non-moving reference regions.

2. The method of claim **1**, further comprising:

displaying the positional differences between the teeth in the first and second models.

3. The method of claim **1**, wherein matching the region of the first computer model with the corresponding region of the second computer model comprises:

placing the first and second computer models in a single coordinate system.

4. The method of claim **1**, wherein calculating the positional differences comprises:

calculating one or more of intrusion, extrusion, translation, rotation, angulation, or inclination of at least some of the teeth in the second computer model, relative to their initial positions in the first computer model.

5. The method of claim **1**, further comprising finding a corrective path for moving at least some teeth from their positions in the second computer model to planned treatment teeth positions.

6. The method of claim **1**, wherein the matched region is selected from the group consisting of one or more rugae on a palate of the jaw, gingiva, bone, a restoration and an implant.

7. The method of claim **1**, further comprising finding a corrective path for moving at least some teeth from their positions in the second computer model to planned treatment teeth positions.

8. The method of claim **7**, further comprising instructions to generate one or more appliances based on the corrective path, each appliance having a geometry selected to progressively reposition at least some of a patient's actual teeth.

9. The method of claim **8**, wherein the appliances comprise polymeric shell appliances.

10. A system for matching computer models of a jaw, the system comprising:

means for loading a first computer model of a jaw having teeth in initial positions

means for loading a second computer model of the jaw, wherein positions of at least some of the teeth in the second computer model are different than the initial positions;

means for identifying at least one reference point on a region of the first computer model, the region comprising a portion of the jaw other than the teeth;

means for identifying a corresponding reference point on a corresponding region of the second computer model for each point identified on the first model;

means for matching the region of the first computer model with the corresponding region of the second computer model, using the identified reference points;

means for matching the first and second computer models as a whole, using the matched regions; and

means for calculating positional differences between the teeth in their initial positions and the teeth in their positions in the second computer model, using the matched regions as non-moving reference regions.

11. The system of claim **10**, further comprising:

means for displaying the positional differences between the teeth in the first and second models.

12. The system of claim **10**, wherein the means for matching the region of the first computer model with the corresponding region of the second computer model comprises:

means for placing the first and second computer models in a single coordinate system.

13. The system of claim **10**, wherein the means for calculating the positional differences comprises:

means for calculating one or more of intrusion, extrusion, translation, rotation, angulation, or inclination of at least some of the teeth in the second computer model, relative to their initial positions in the first computer model.

14. The system of claim **10**, further comprising means for finding a corrective path for moving at least some teeth from their positions in the second computer model to planned treatment teeth positions.

15. The system of claim **10**, wherein the matched region is selected from the group consisting of one or more rugae on a palate of the jaw, gingiva, bone, restoration and an implant.

16. The system of claim **10**, further comprising means for finding a corrective path for moving at least some teeth from their positions in the second computer model to planned treatment teeth positions.

17. The system of claim **16**, further comprising means for generating one or more appliances based on the corrective path, each appliance having a geometry selected to progressively reposition at least some of a patient's actual teeth.

18. The method of claim **17**, wherein the appliances comprise polymeric shell appliances.

19. A tangible computer readable medium containing code for matching computer models of a jaw, the tangible computer readable medium comprising instructions to:

load a first computer model of a jaw having teeth in initial positions;

load a second computer model of the jaw, wherein positions of at least some of the teeth in the second computer model are different than the initial positions;

identify at least one reference point on a region of the first computer model, the region comprising a portion of the model other than the teeth;

identify a corresponding reference point on a corresponding region of the second computer model for each point identified on the first model;

march the region of the first computer model with the corresponding region of the second computer model, using the identified reference points;

match the first and second computer models as a whole, using the matched regions; and

calculate positional differences between the teeth in their initial positions and the teeth in their positions in the second computer model, using the matched regions as non-moving reference regions.

20. The medium of claim **19**, further comprising instructions to:

display the positional differences between the teeth in the first and second models.

21. The medium of claim **19**, further comprising instructions to:

place two jaw impressions in a single coordinate system.

22. The medium of claim **19**, further comprising instructions to:

calculate one or more of intrusion, extrusion, translation, rotation, angulation, or inclination of at least some of the teeth in the second computer model, relative to their positions in the first computer model.

23. The medium of claim **19**, further comprising instructions to find a corrective path for moving at least some teeth from their positions in the second computer model to planned treatment teeth positions.

24. The medium of claim **23**, further comprising instructions to generate one or more appliances based on the corrective path, each appliance having a geometry selected to progressively reposition at least some of a patient's actual teeth.

25. The medium of claim **24**, wherein the appliances comprise polymeric shell appliances.

26. The medium of claim **19**, wherein the watched region is selected from the group consisting of one or more rugae on a palate of the jaw, gingiva, bone, a restoration, and an implant.

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