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(54) HAPTIC GUIDANCE SYSTEM AND METHOD

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(73) Assignee: **MAKO Surgical Corporation**

(21) Appl. No.: **11/357,197**

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Related U.S. Application Data

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Continuation-in-part of application No. 10/384,194, filed on Mar. 6, 2003.

Continuation-in-part of application No. 10/384,078, filed on Mar. 6, 2003.

Continuation-in-part of application No. 10/384,077, filed on Mar. 6, 2003.

Continuation-in-part of application No. 10/384,072, filed on Mar. 6, 2003.

Said application No. 10/621,119 is a continuation-in-part of application No. 10/384,072, filed on Mar. 6, 2003.

(60) Provisional application No. 60/759,186, filed on Jan. 17, 2006. Provisional application No. 60/655,642, filed on Feb. 22, 2005. Provisional application No. 60/362,368, filed on Mar. 6, 2002. Provisional application No. 60/362,368, filed on Mar. 6, 2002. Provisional application No. 60/362,368, filed on Mar. 6, 2002.

Publication Classification

(51) **Int. Cl.**
A61B 5/05 (2006.01)

(52) **U.S. Cl.** **600/424**

(57) **ABSTRACT**

A surgical apparatus includes a surgical device, configured to be manipulated by a user to perform a procedure on a patient, and a computer system. The computer system is programmed to implement control parameters for controlling the surgical device to provide at least one of haptic guidance to the user and a limit on user manipulation of the surgical device, based on a relationship between an anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the surgical device, and to adjust the control parameters in response to movement of the anatomy during the procedure.

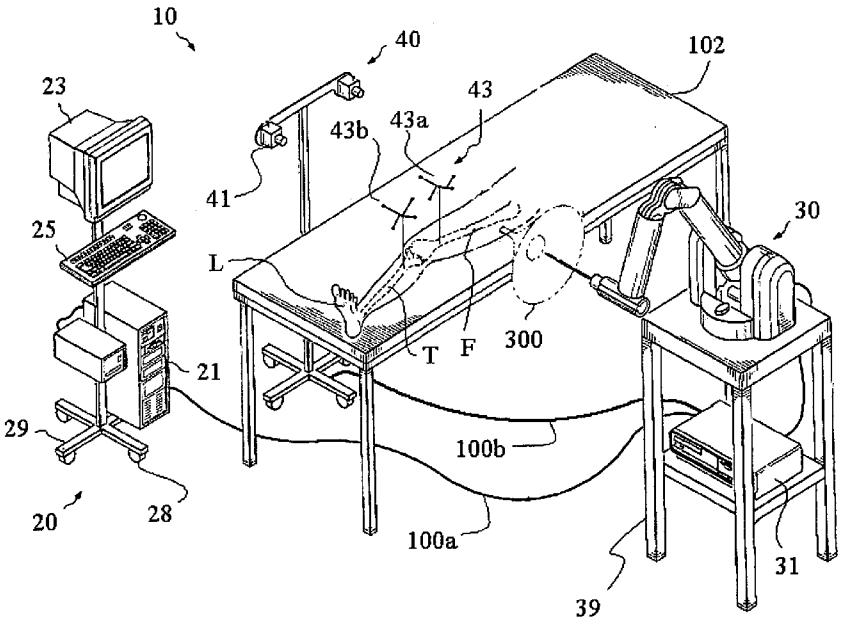


Exhibit 1111
DENTAL IMAGING
IPR2023-00111

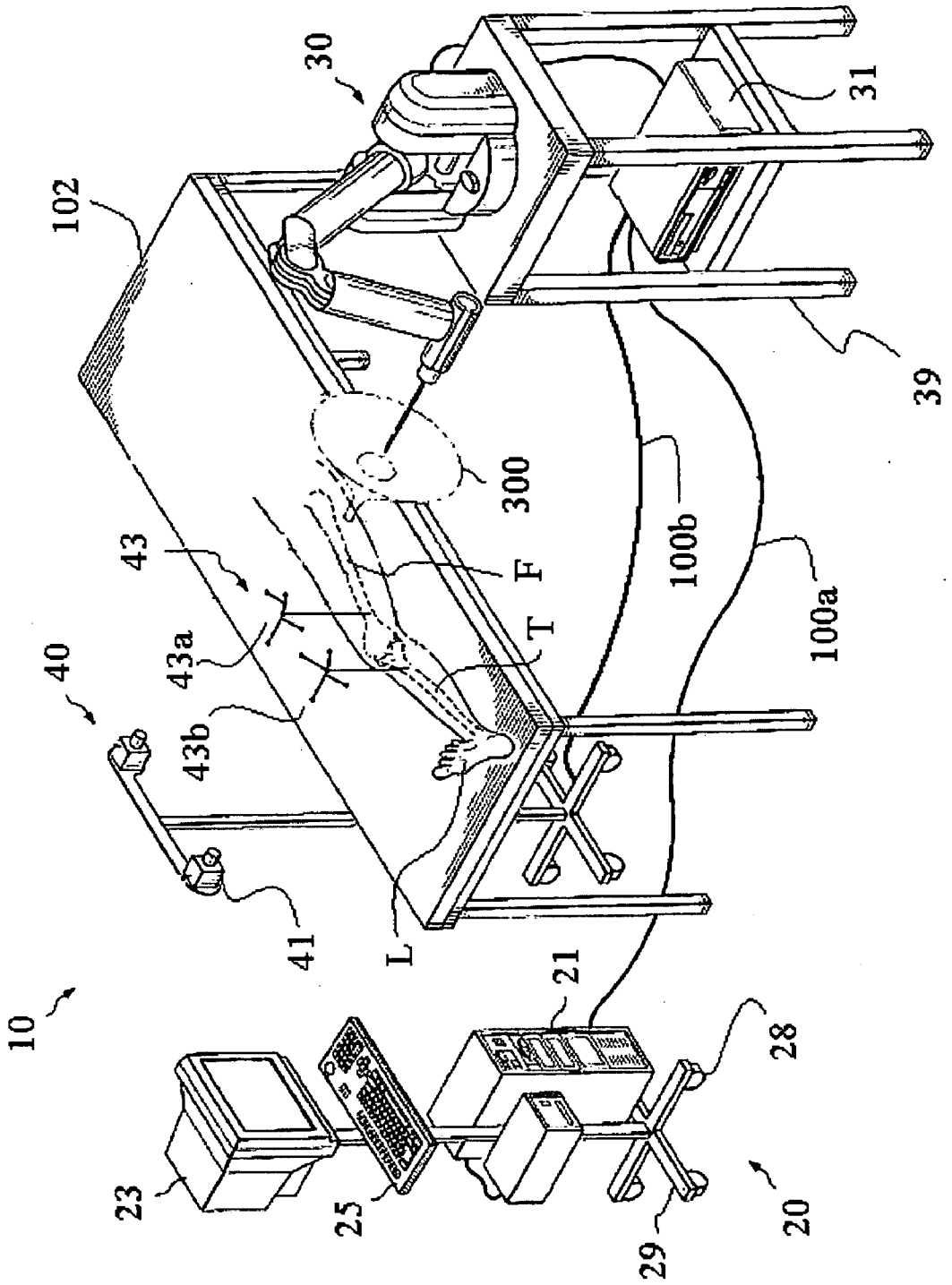


FIG. 1

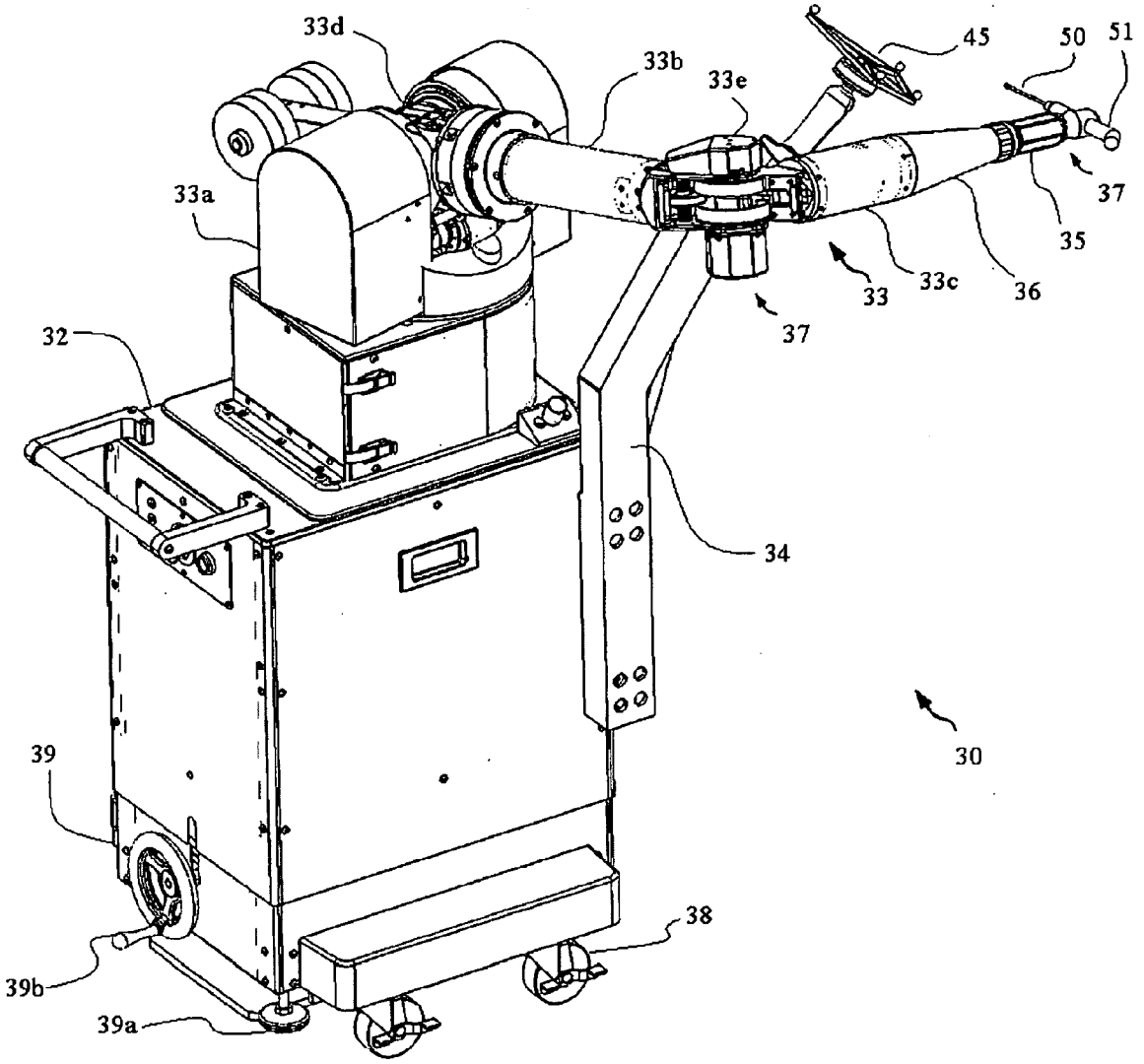


FIG. 2A

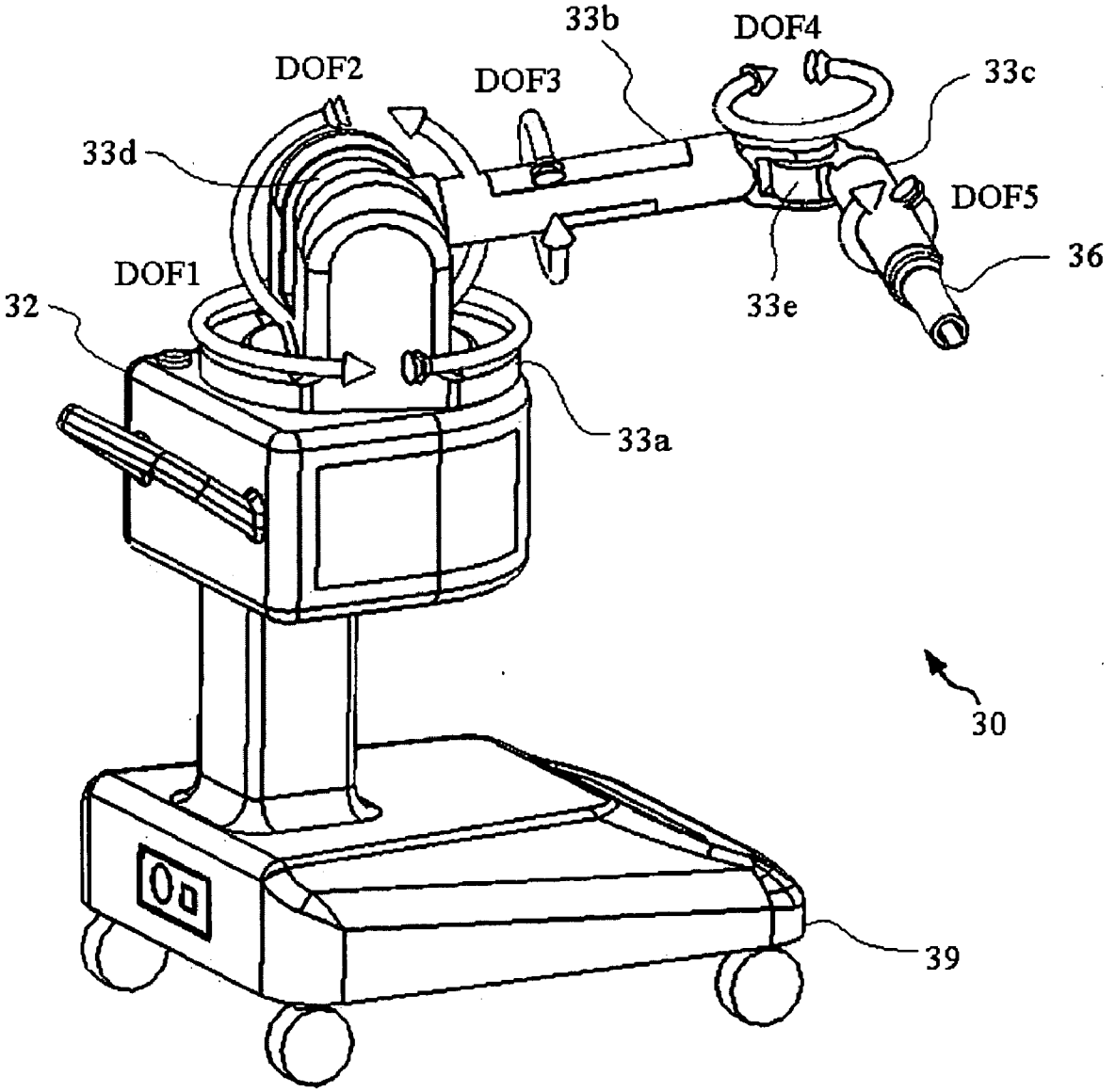


FIG. 2B

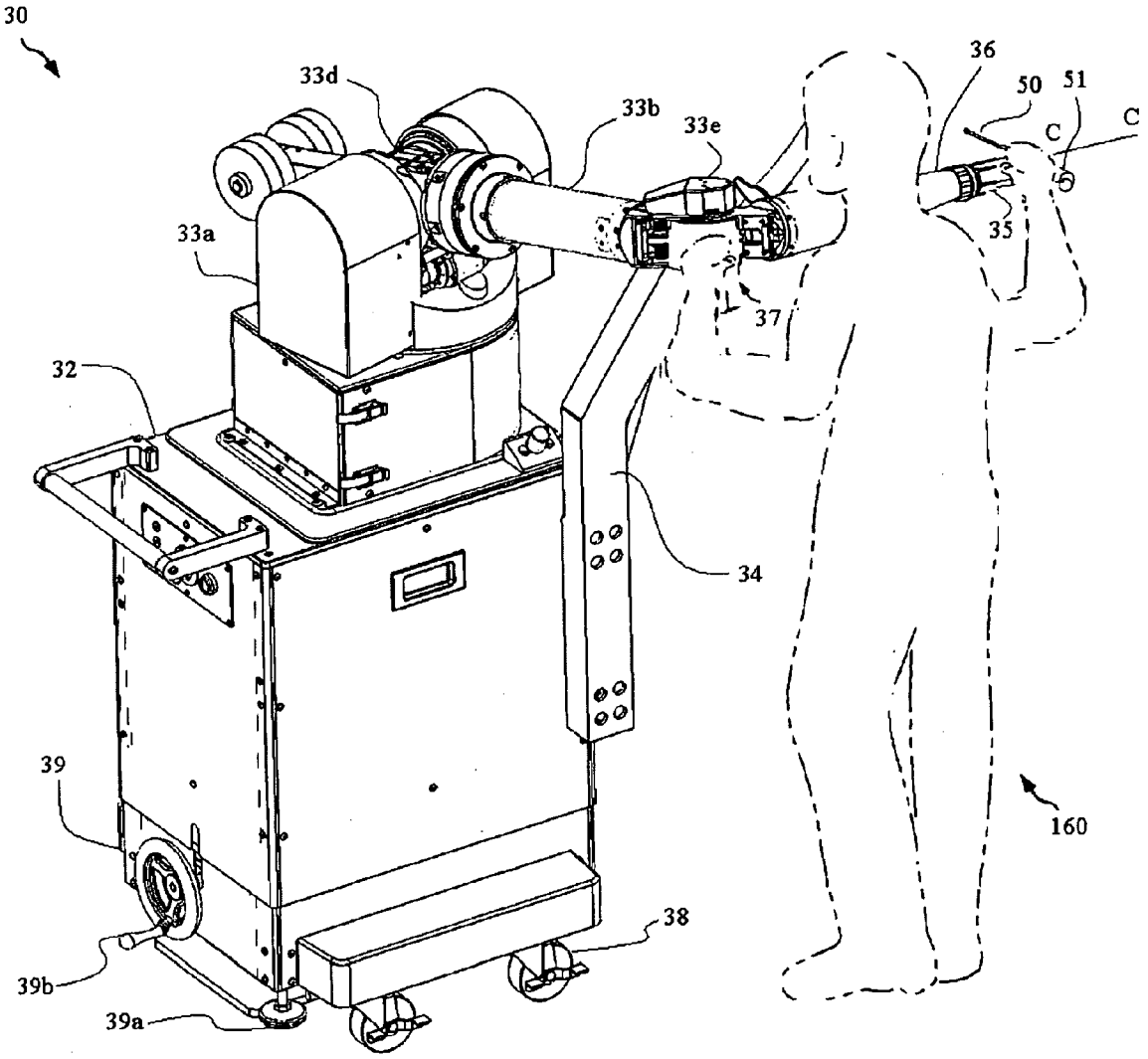


FIG. 2C

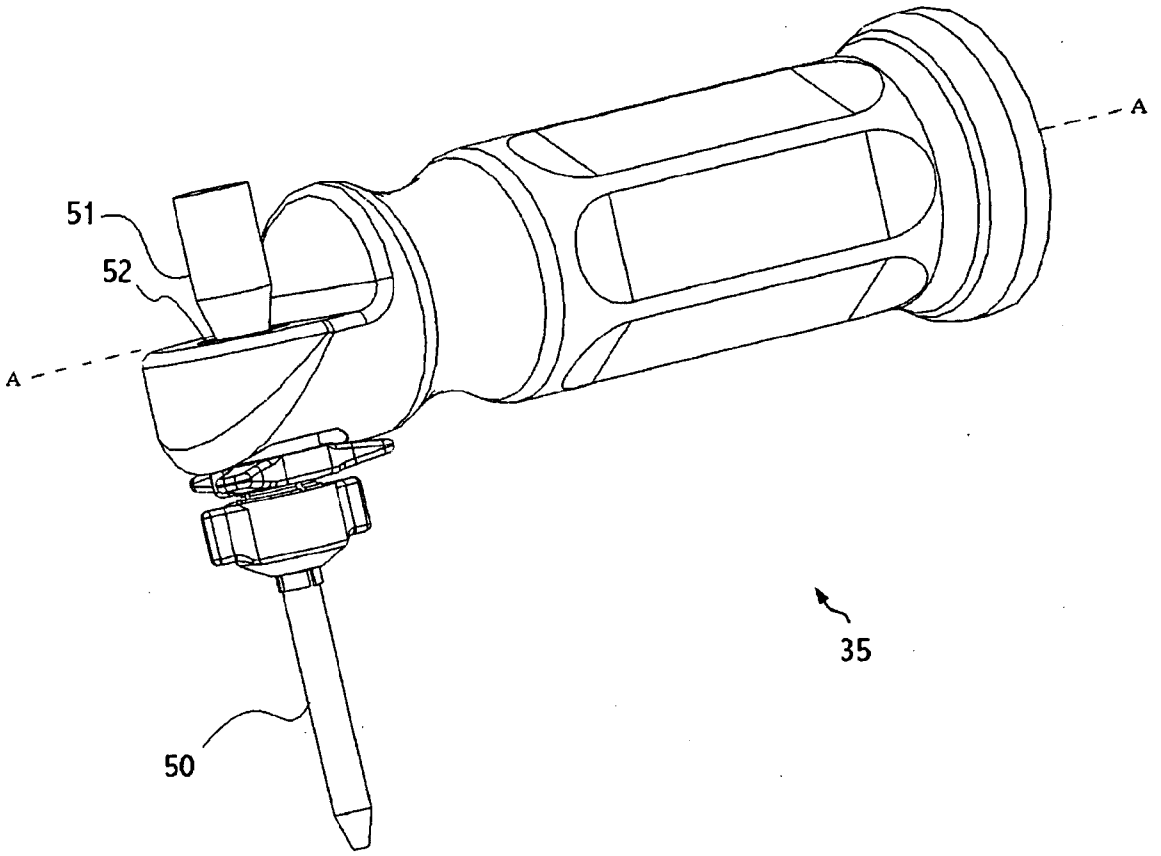


FIG. 3

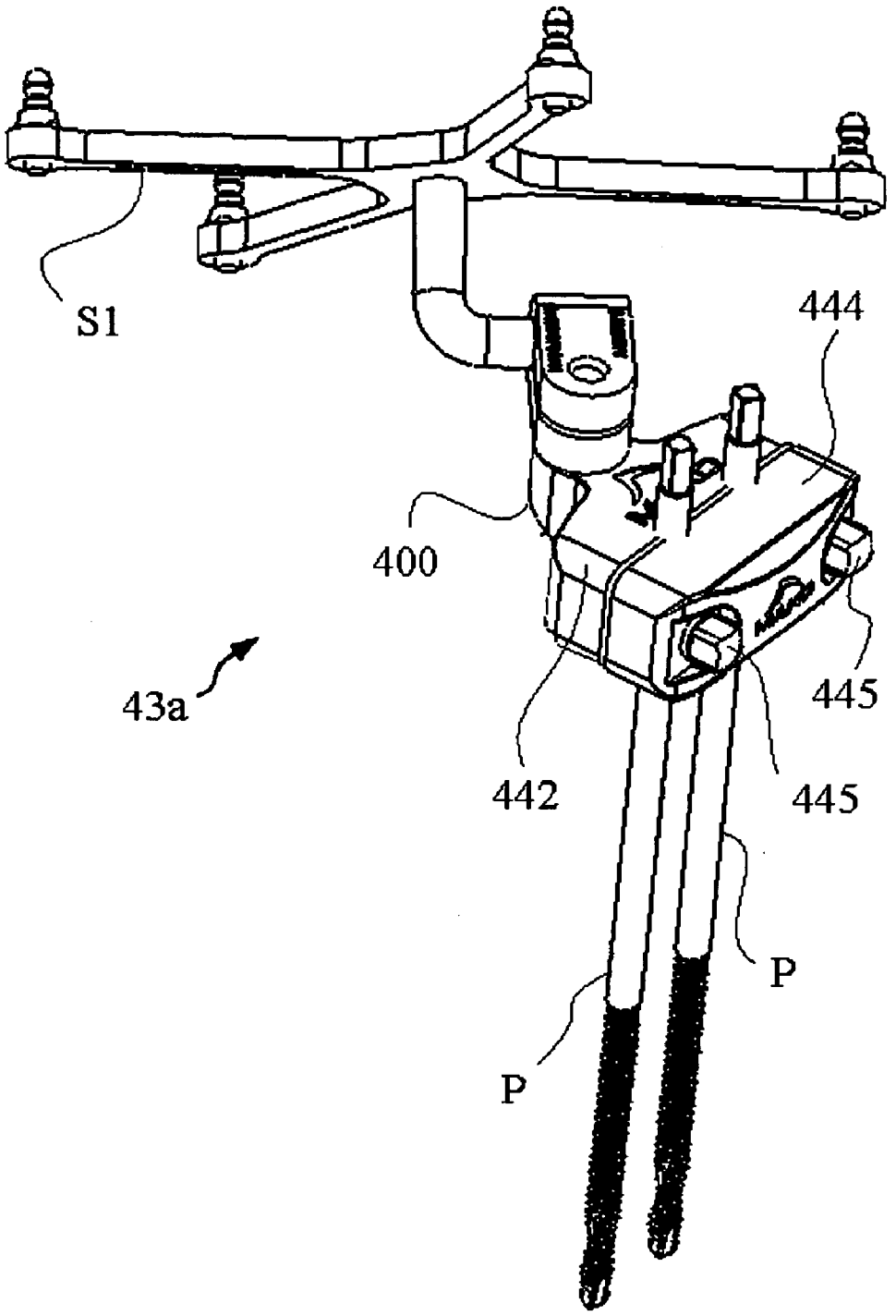


FIG. 4

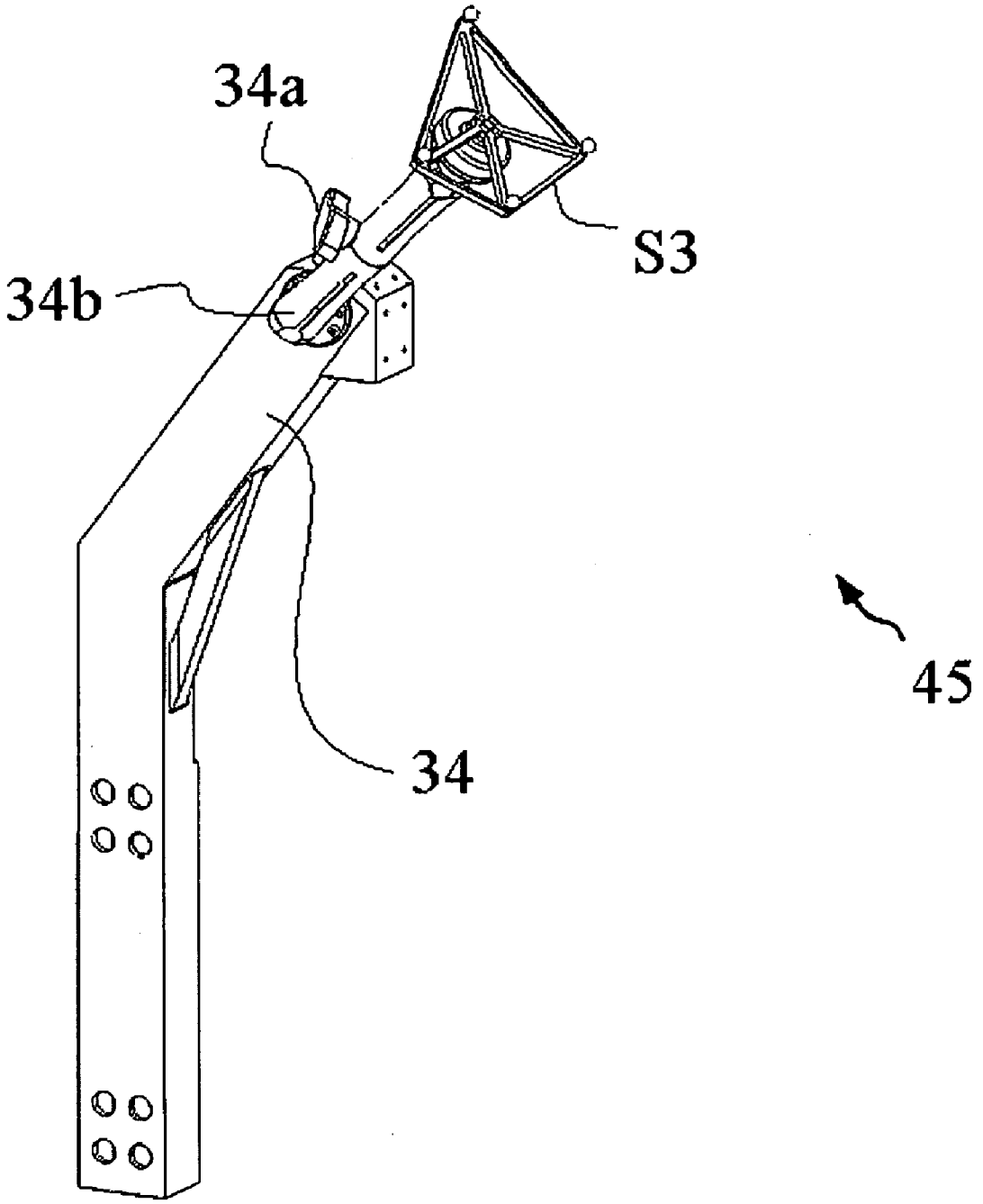


FIG. 5

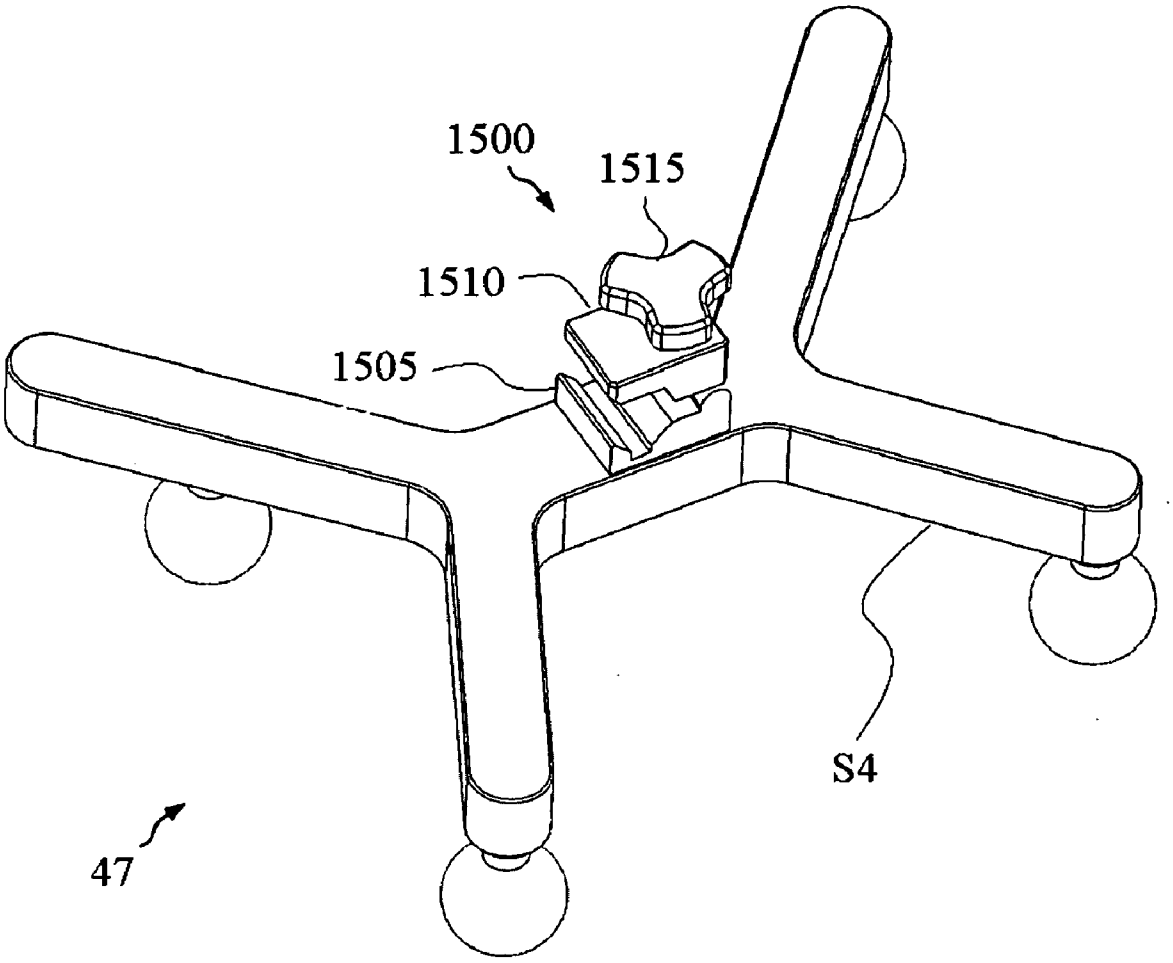


FIG. 6A

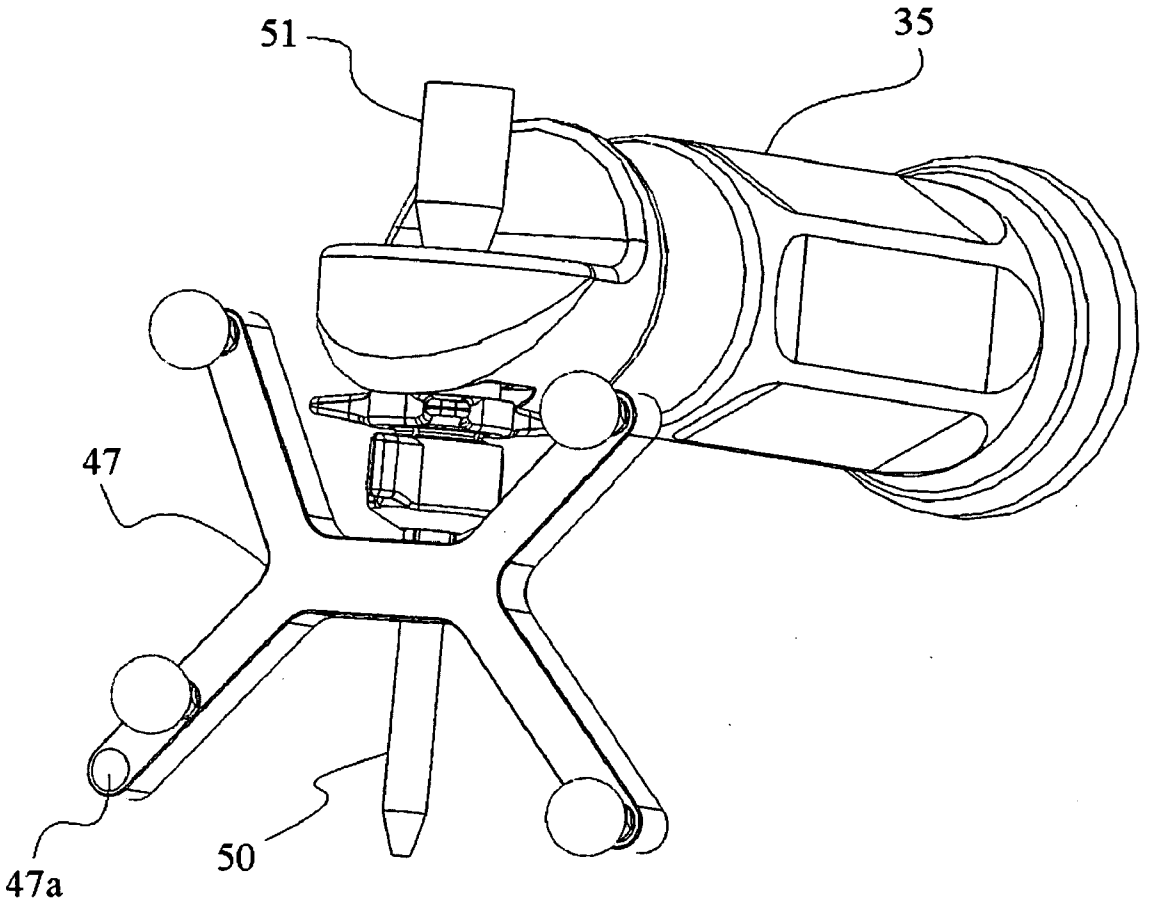


FIG. 6B

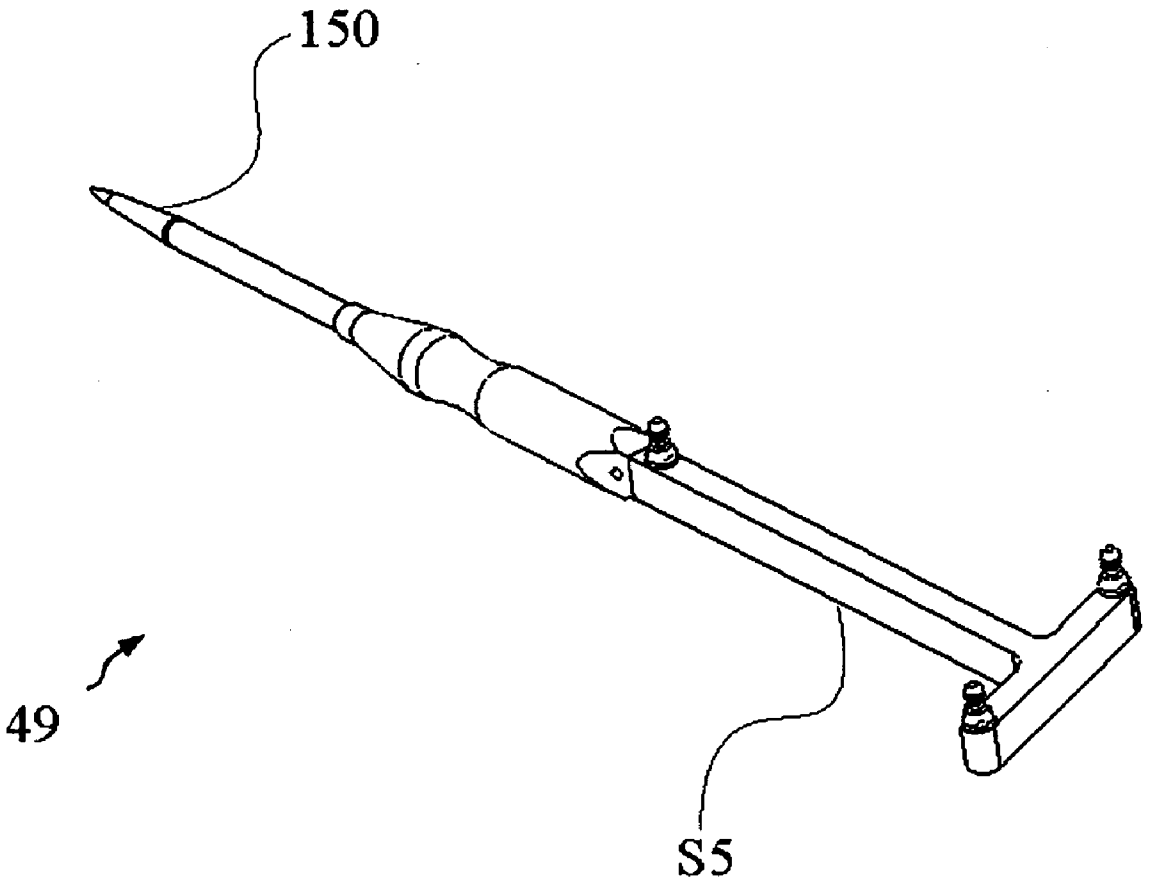


FIG. 7

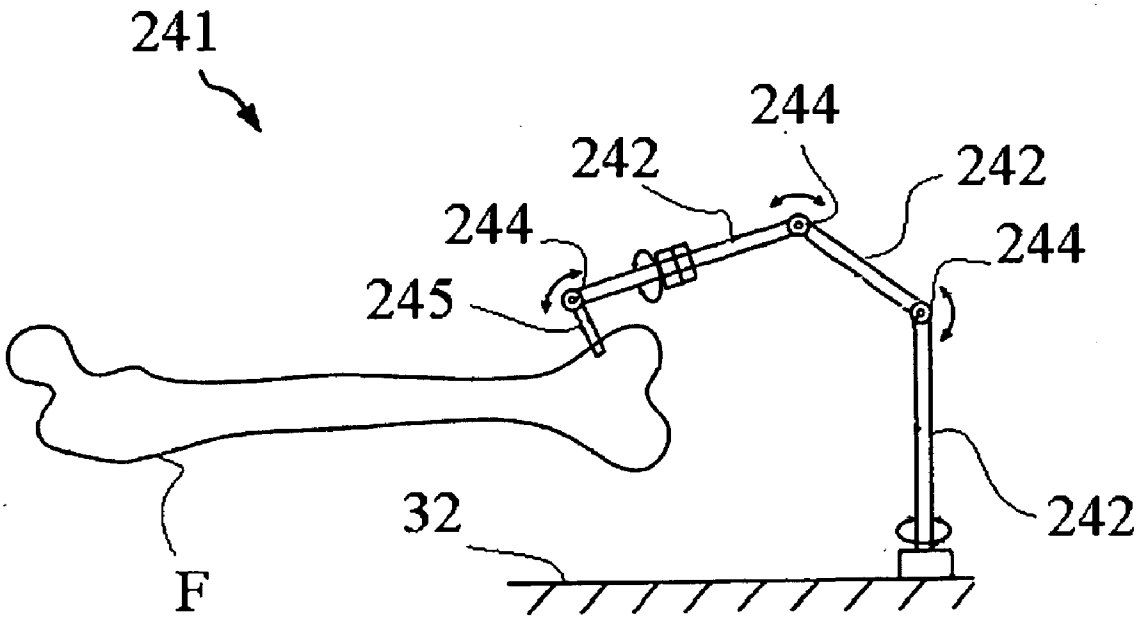


FIG. 8

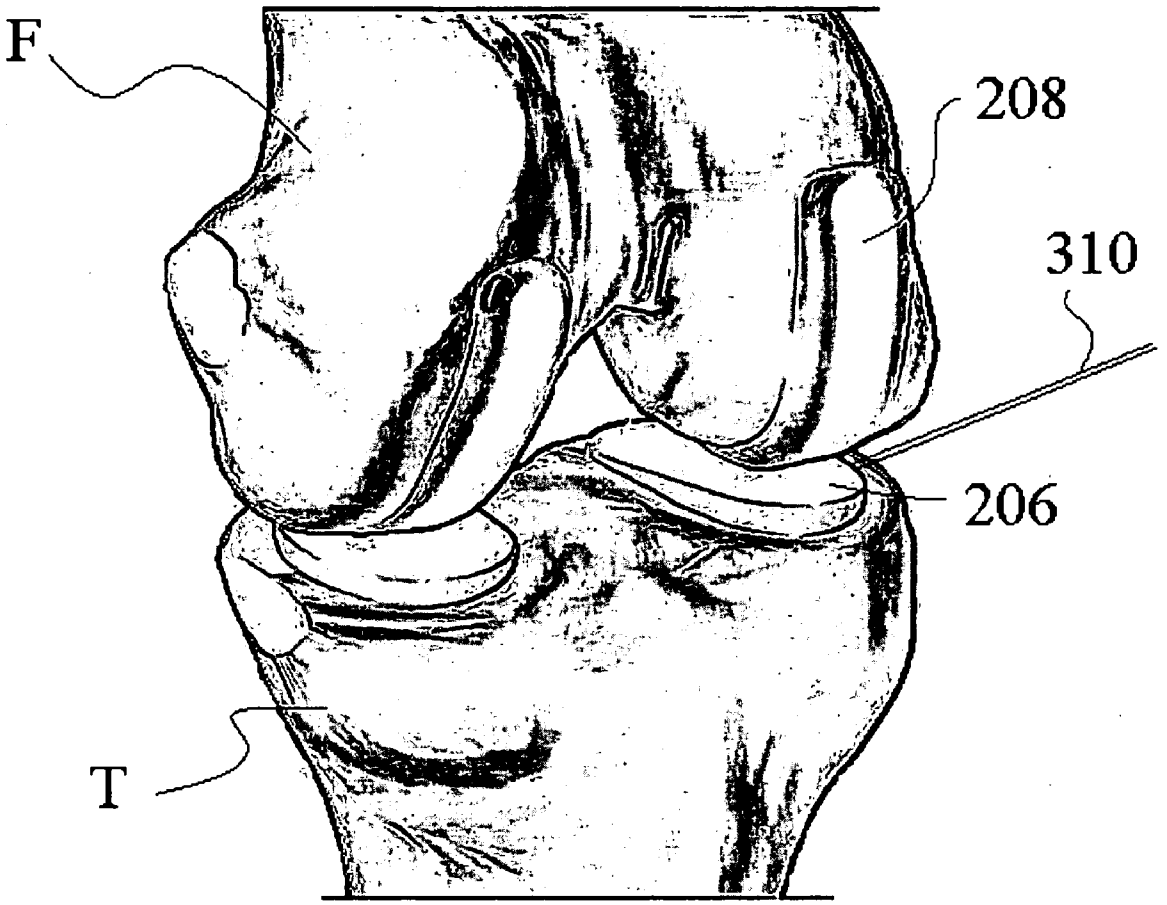


FIG. 9

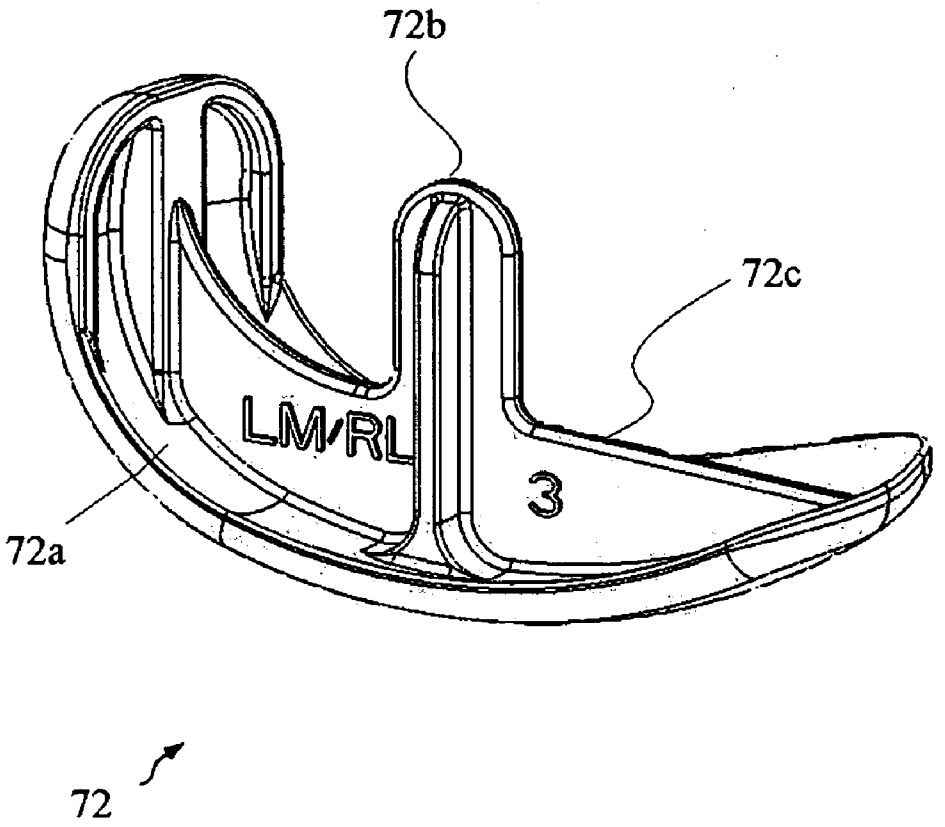


FIG. 10A

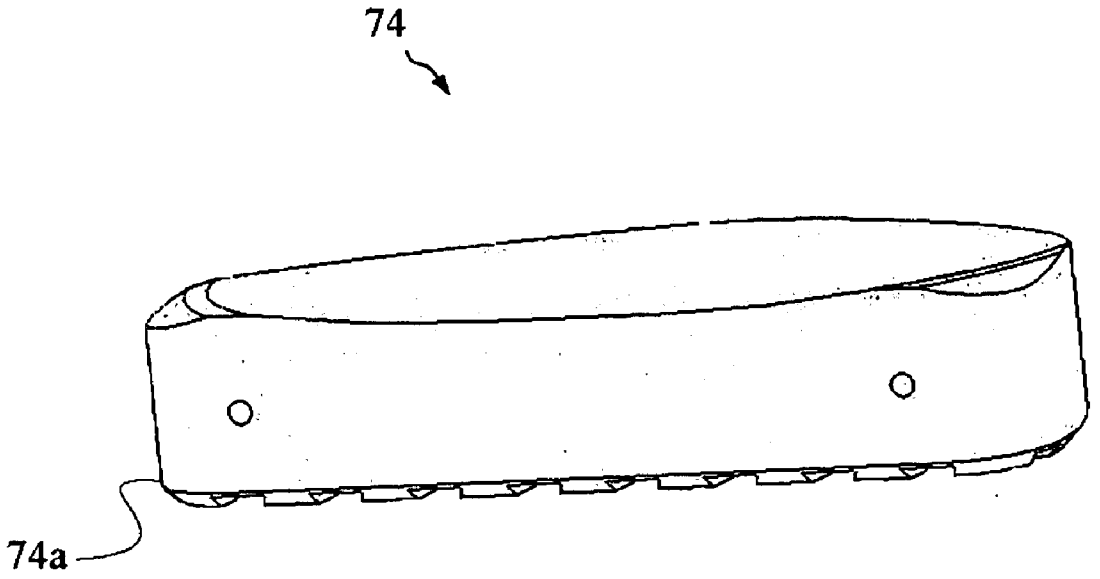


FIG. 10B

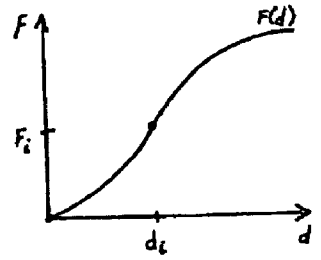


FIG. 11A

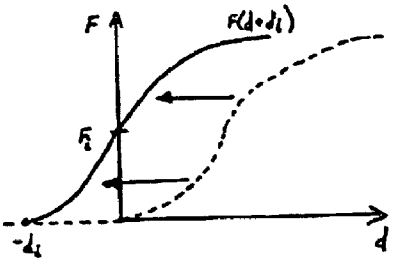


FIG. 11B

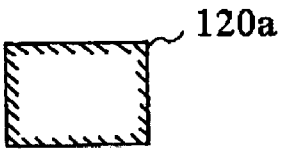


FIG. 11C

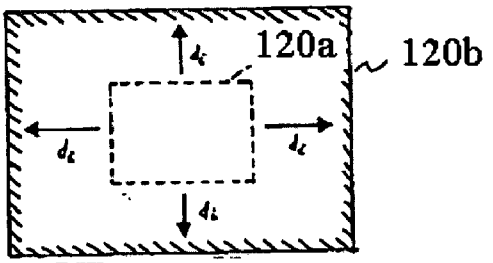


FIG. 11D

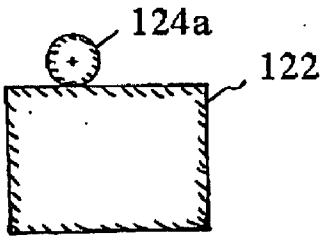


FIG. 11E

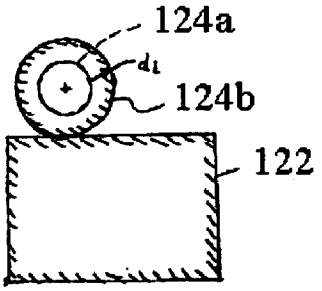


FIG. 11F

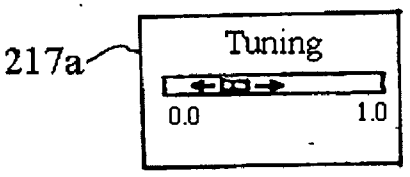


FIG. 11G

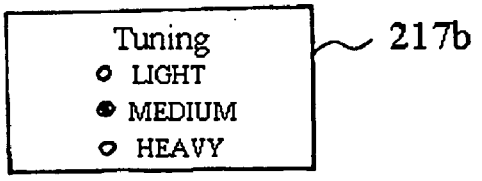


FIG. 11H

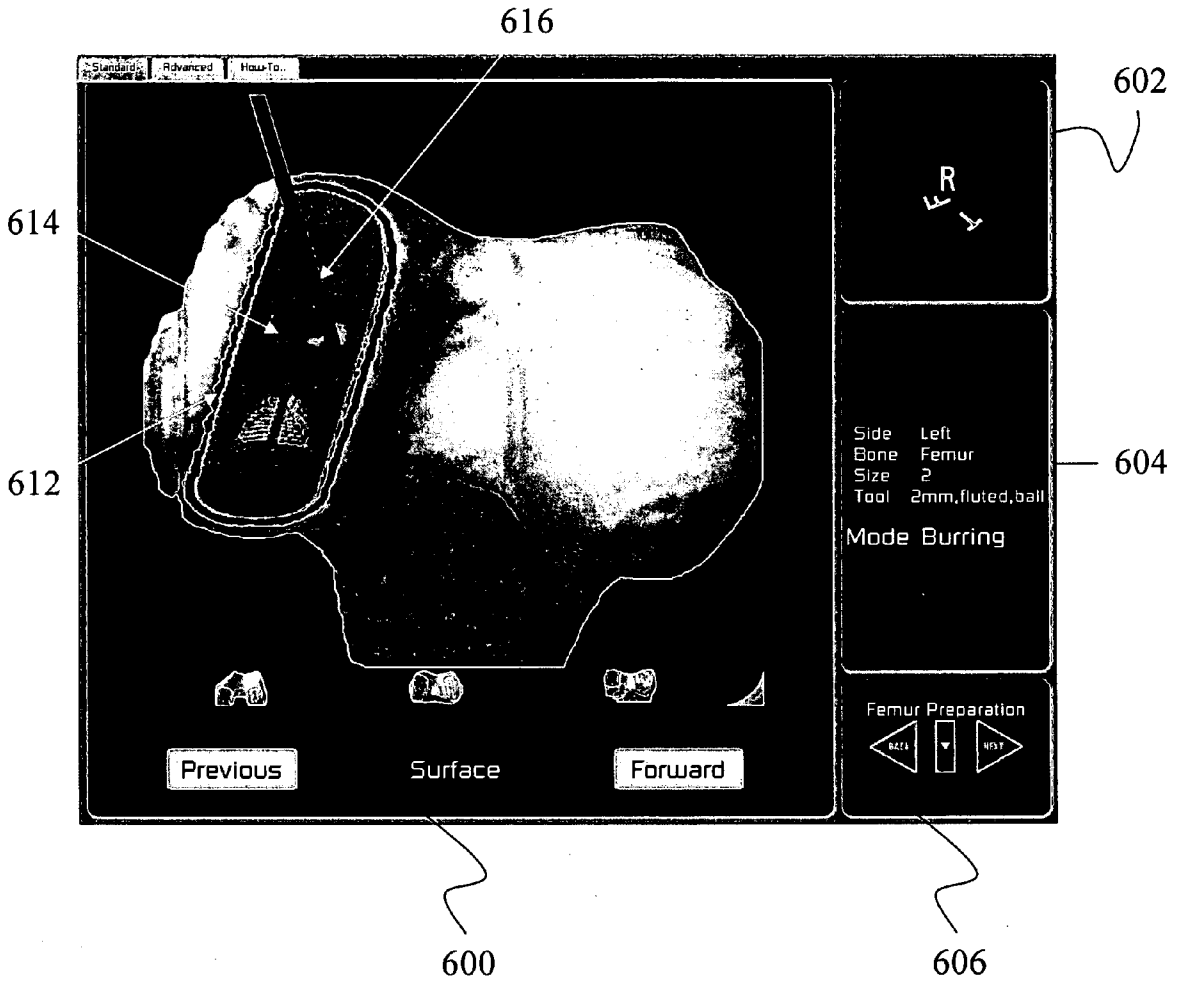

616
602
614
612
604
Standard
Advanced
How-To..
Side Left
Bone Femur
Size 2
Tool 2mm,fluted,ball
Mode Burring
Femur Preparation
Previous
Surface
Forward
600
606

FIG. 12

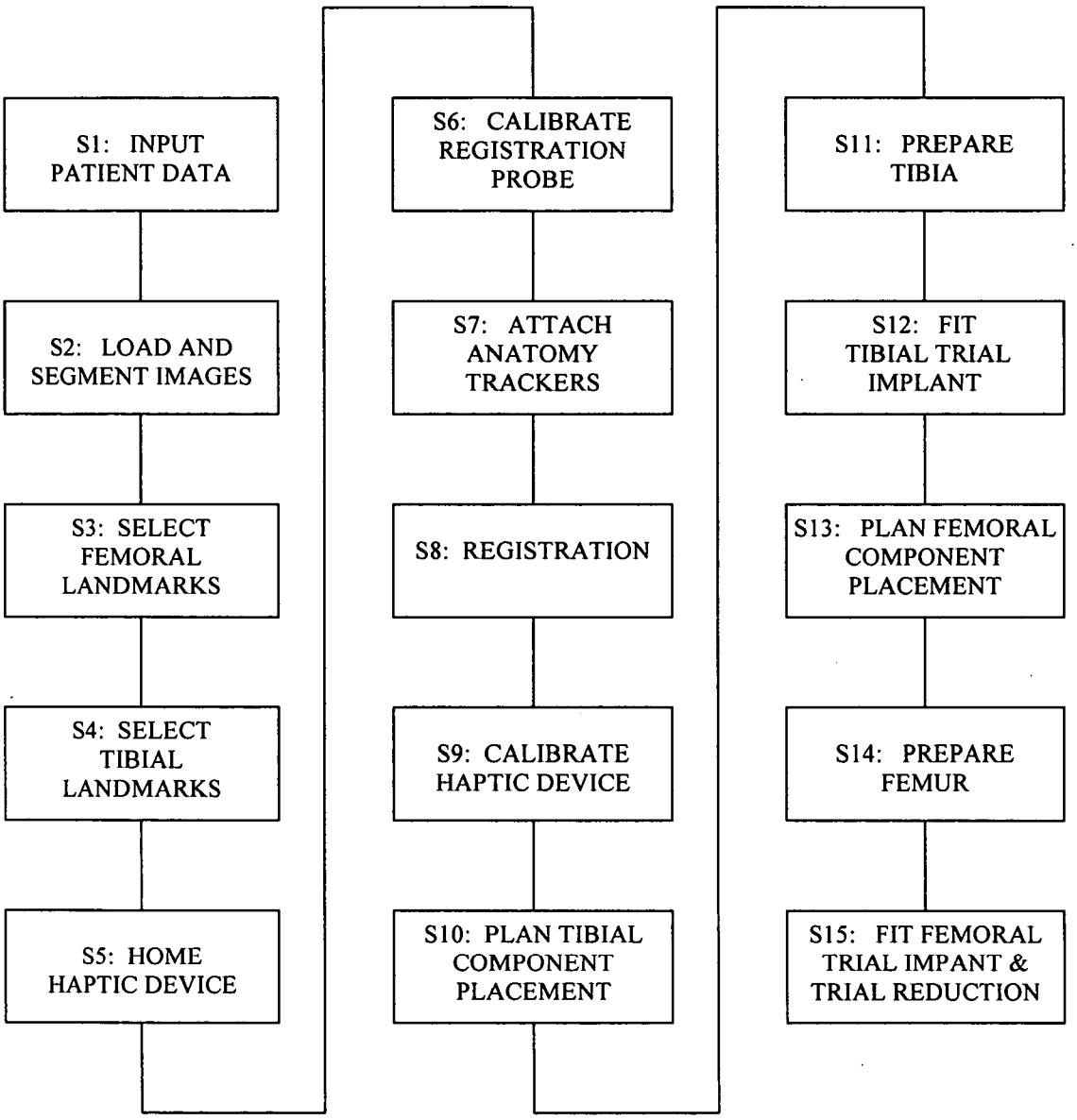

S1: INPUT PATIENT DATA
S2: LOAD AND SEGMENT IMAGES
S3: SELECT FEMORAL LANDMARKS
S4: SELECT TIBIAL LANDMARKS
S5: HOME HAPTIC DEVICE
S6: CALIBRATE REGISTRATION PROBE
S7: ATTACH ANATOMY TRACKERS
S8: REGISTRATION
S9: CALIBRATE HAPTIC DEVICE
S10: PLAN TIBIAL COMPONENT PLACEMENT
S11: PREPARE TIBIA
S12: FIT TIBIAL TRIAL IMPLANT
S13: PLAN FEMORAL COMPONENT PLACEMENT
S14: PREPARE FEMUR
S15: FIT FEMORAL TRIAL IMPANT & TRIAL REDUCTION

FIG. 13

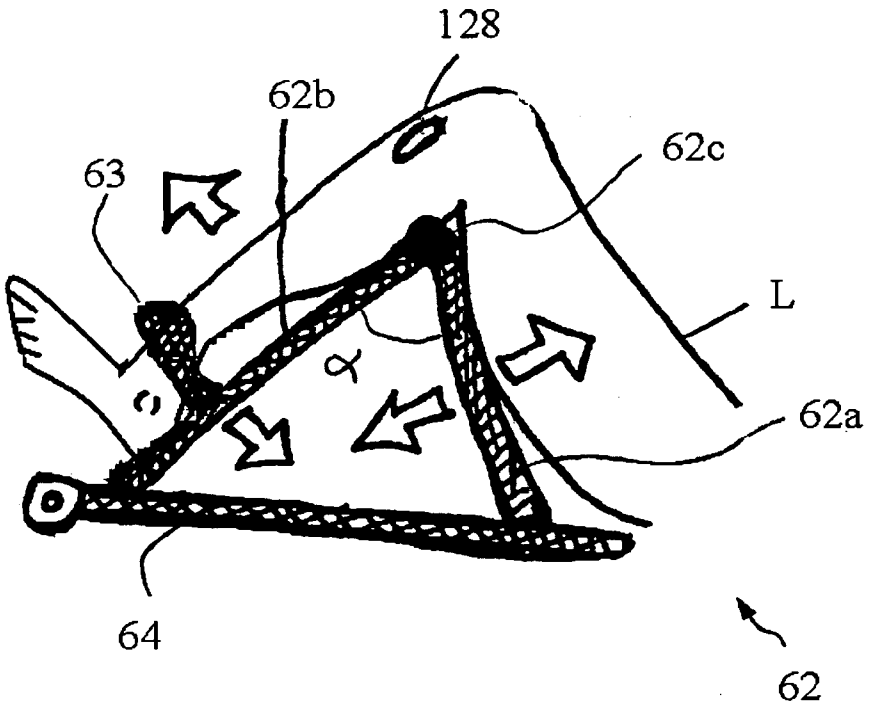


FIG. 14A

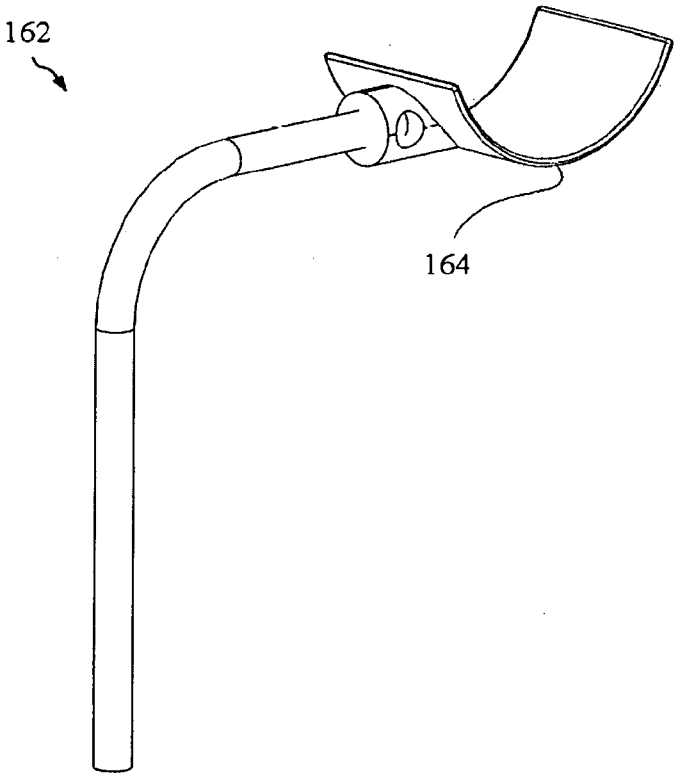
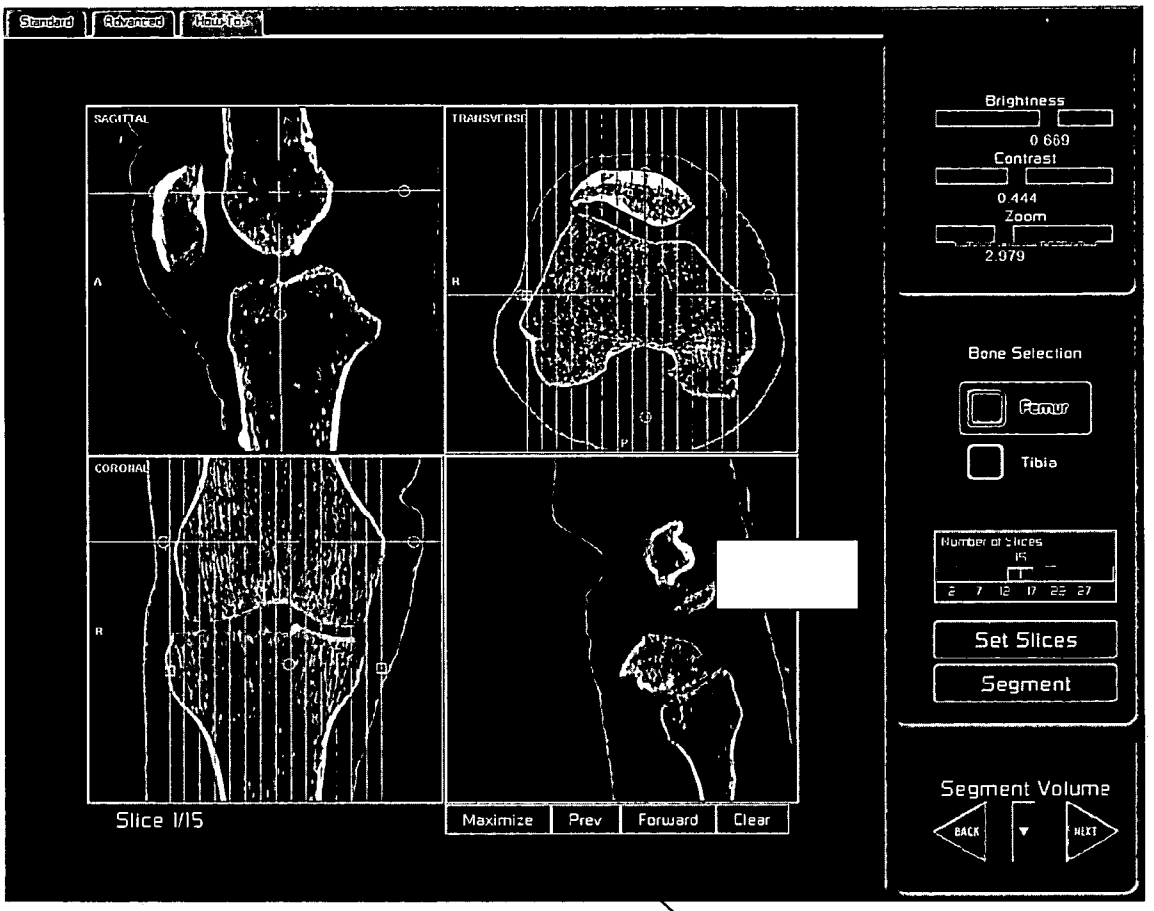
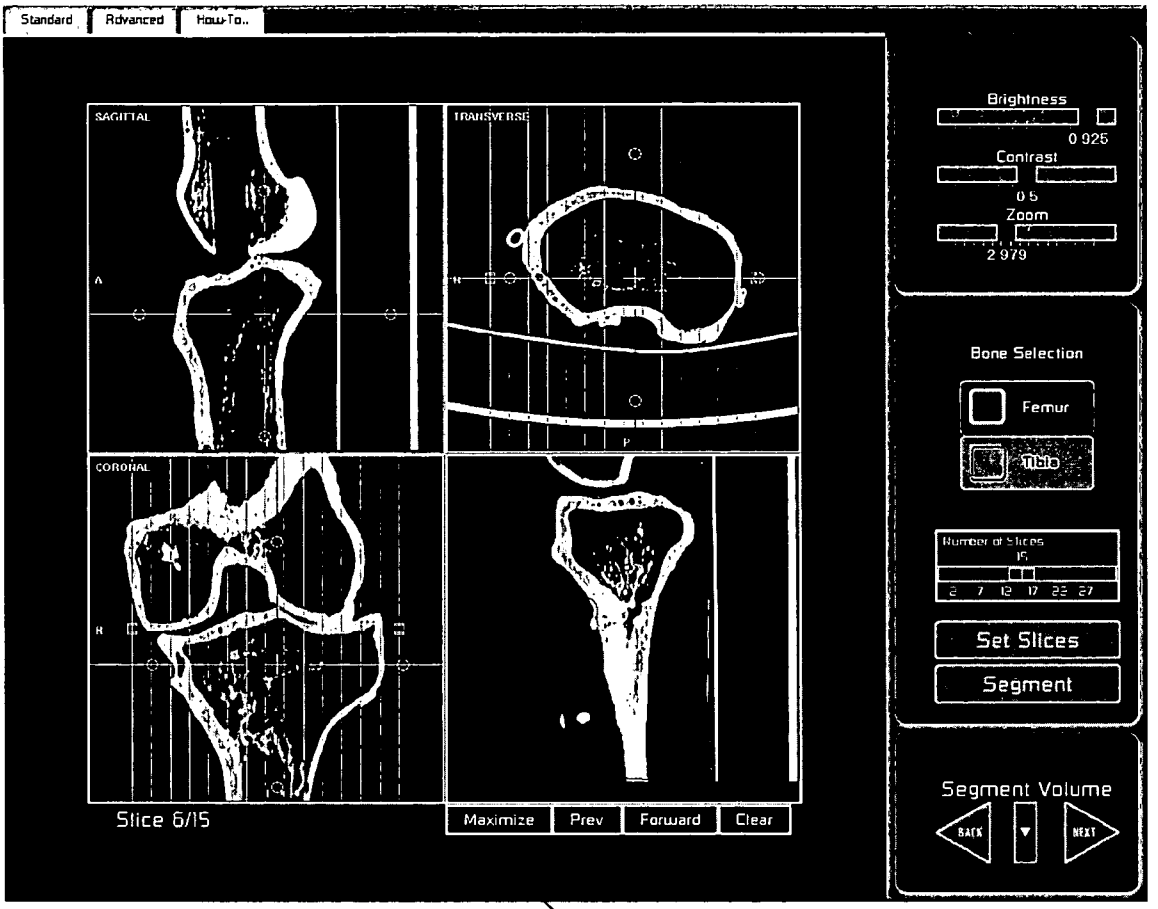


FIG. 14B


Standard
Advanced
SAGITTAL
TRANSVERSE
CORONAL
Slice 1/15
Maximize
Prev
Forward
Clear
Brightness
0.669
Contrast
0.444
Zoom
2.979
Bone Selection
Femur
Tibia
Number of Slices
Set Slices
Segment
Segment Volume
BACK
NEXT

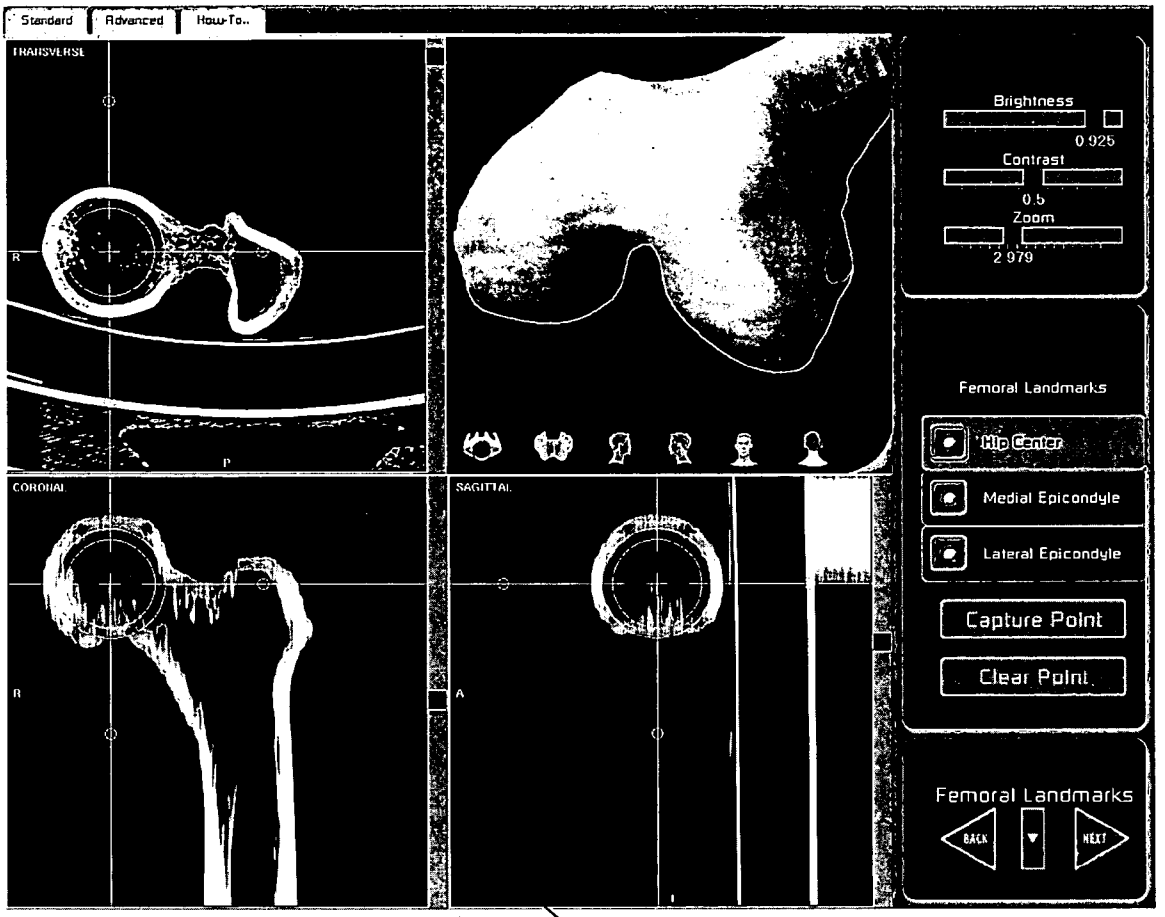
81a

FIG. 15


Standard
Advanced
How-To..
SAGITTAL
TRANSVERSE
CORONAL
Slice 6/15
Maximize
Prev
Forward
Clear
Brightness
0.925
Contrast
0.5
Zoom
2.979
Bone Selection
Femur
Tibia
Number of Slices
16
2 7 12 17 22 27
Set Slices
Segment
Segment Volume
BACK
NEXT

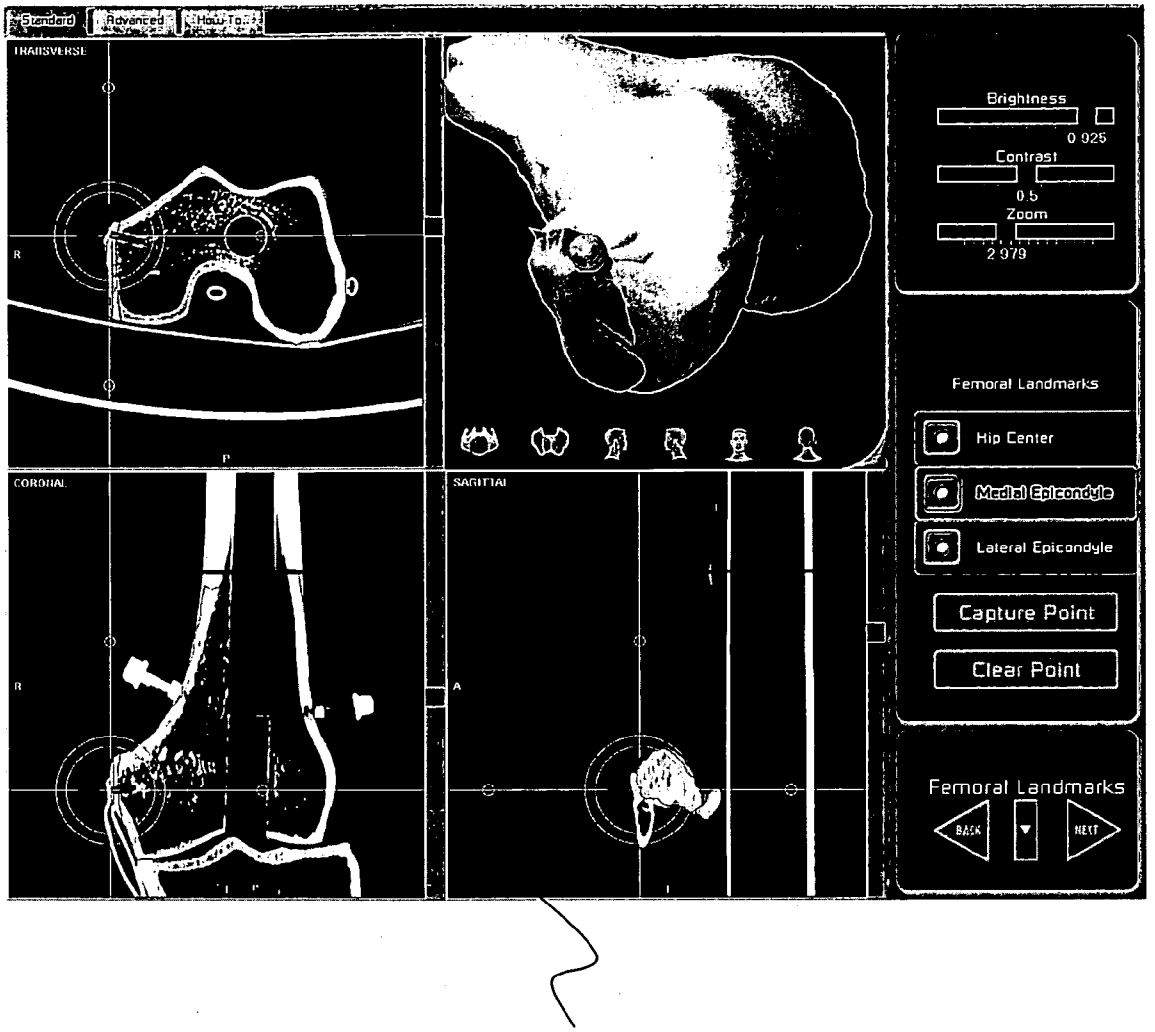
81b

FIG. 16


Standard
Advanced
How-To..
TRANSVERSE
CORONAL
SAGITTAL
Brightness
0.925
Contrast
0.5
Zoom
2.979
Femoral Landmarks
Hip Center
Medial Epicondyle
Lateral Epicondyle
Capture Point
Clear Point
Femoral Landmarks
BACK
NEXT

82a

FIG. 17


Standard
Advanced
How To...
TRANSVERSE
CORONAL
SAGITTAL
Brightness
0.925
Contrast
0.5
Zoom
2.979
Femoral Landmarks
Hip Center
Medial Epicondyle
Lateral Epicondyle
Capture Point
Clear Point
Femoral Landmarks
BACK
NEXT

82b

FIG. 18

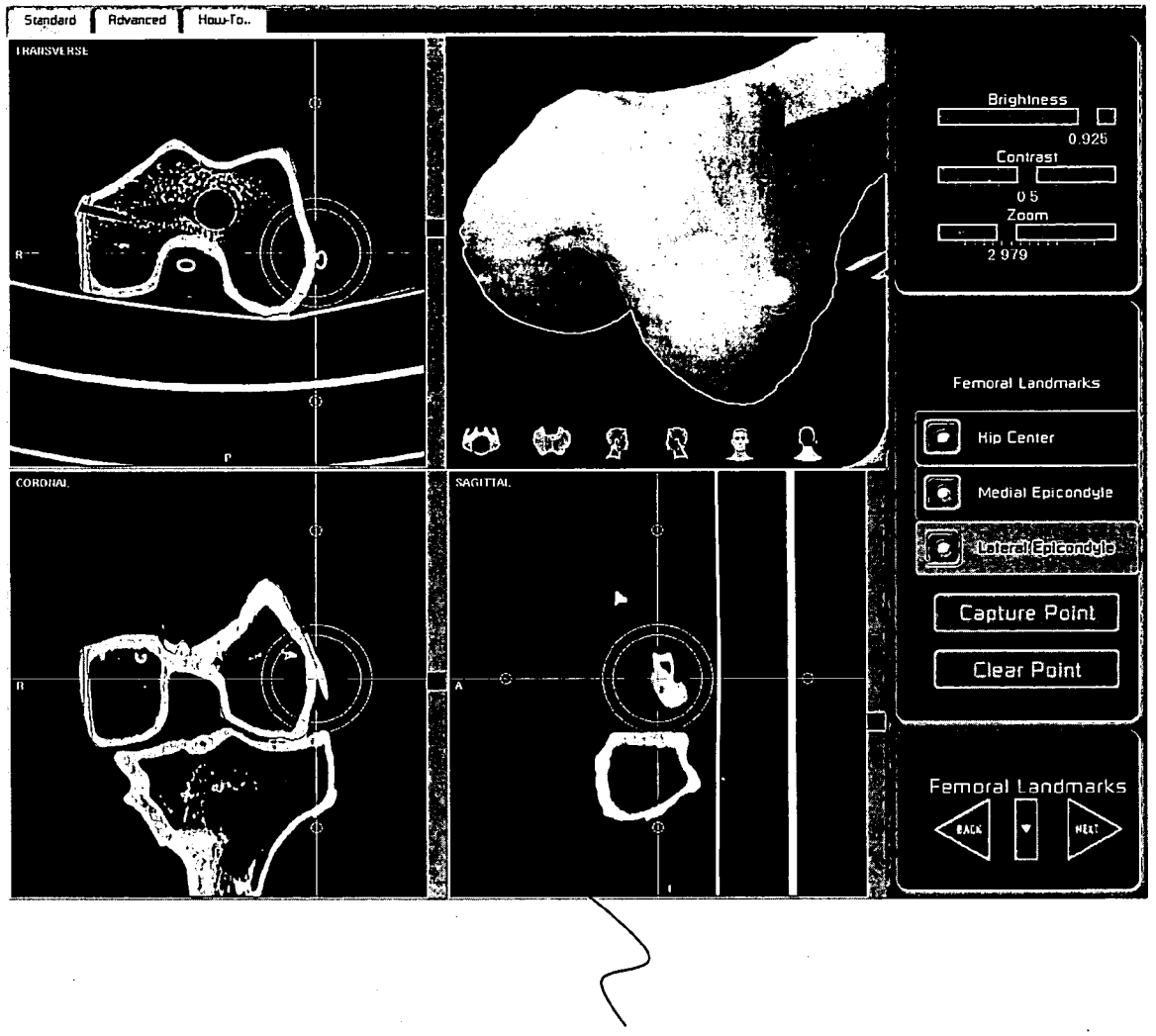

Standard
Advanced
How-To..
TRANSVERSE
CORONAL
SAGITTAL
Brightness
0.925
Contrast
0.5
Zoom
2.979
Femoral Landmarks
Hip Center
Medial Epicondyle
Lateral Epicondyle
Capture Point
Clear Point
Femoral Landmarks
BACK
NEXT
82c

FIG. 19

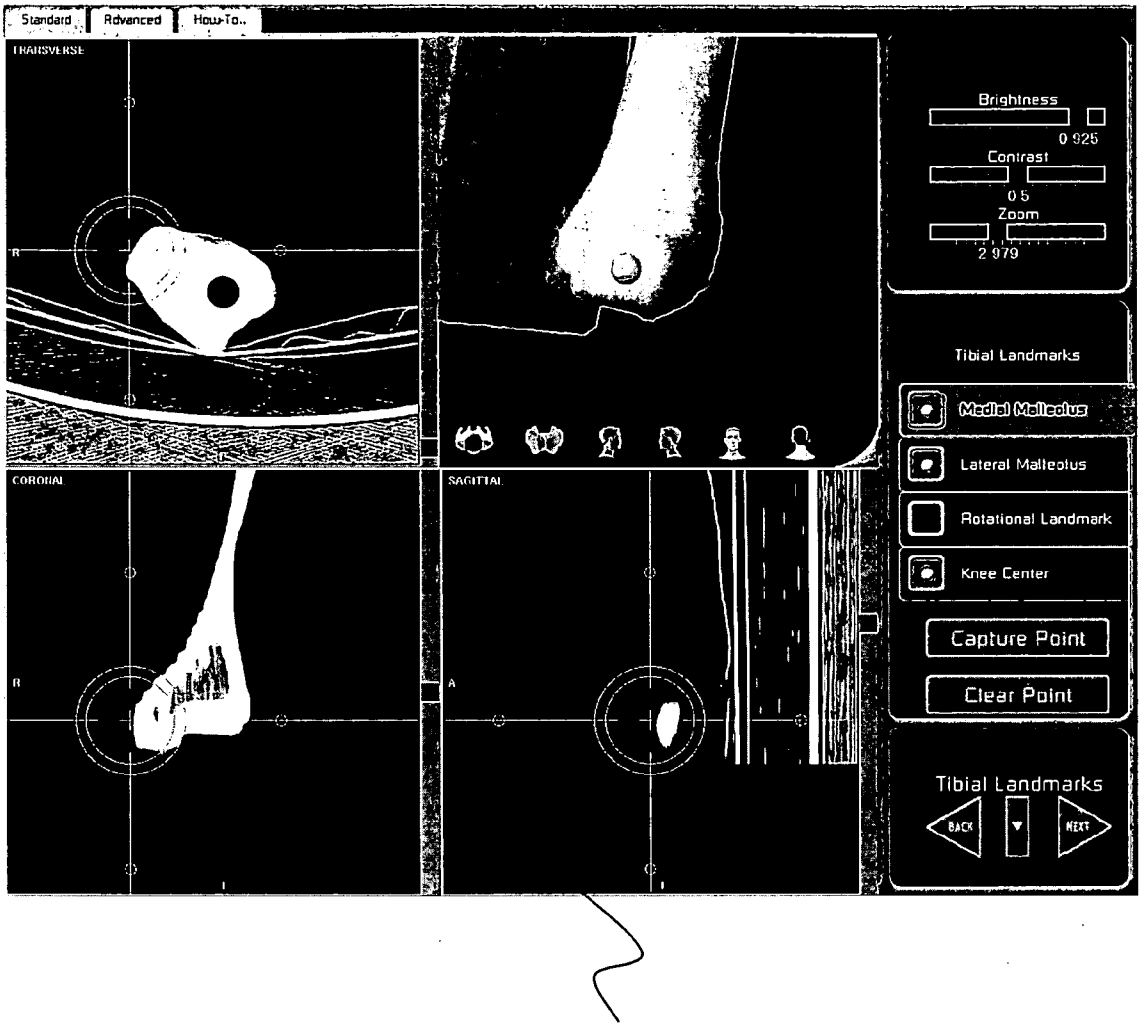
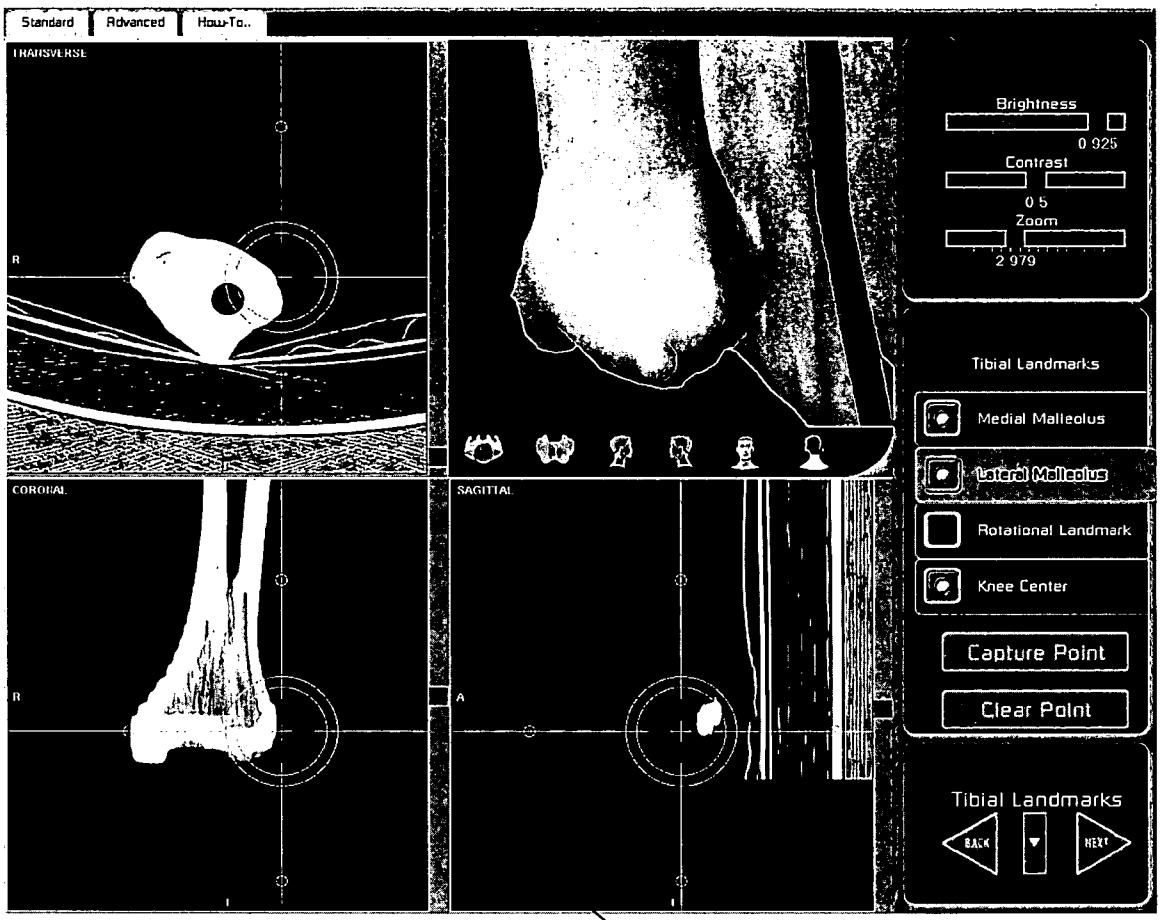

Standard
Advanced
How-To..
TRANSVERSE
CORONAL
SAGITTAL
Brightness
0.925
Contrast
0.5
Zoom
2.979
Tibial Landmarks
Medial Malleolus
Lateral Malleolus
Rotational Landmark
Knee Center
Capture Point
Clear Point
Tibial Landmarks
BACK
NEXT
83a

FIG. 20


Standard
Advanced
How-To..
TRANSVERSE
R
CORONAL
R
SAGITTAL
A
Brightness
0.925
Contrast
0.5
Zoom
2.979
Tibial Landmarks
Medial Malleolus
Lateral Malleolus
Rotational Landmark
Knee Center
Capture Point
Clear Point
Tibial Landmarks
BACK
NEXT

83b

FIG. 21

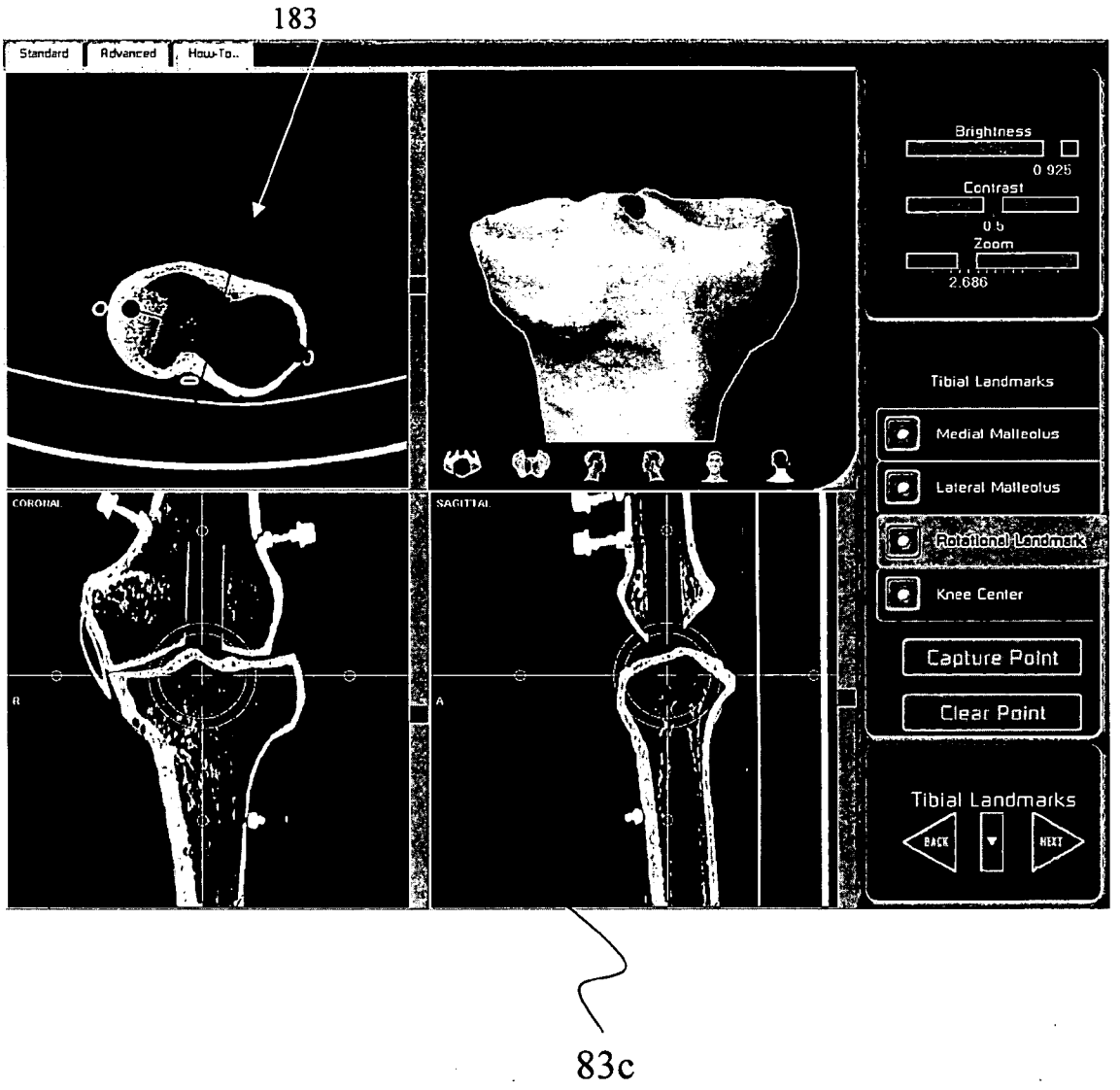
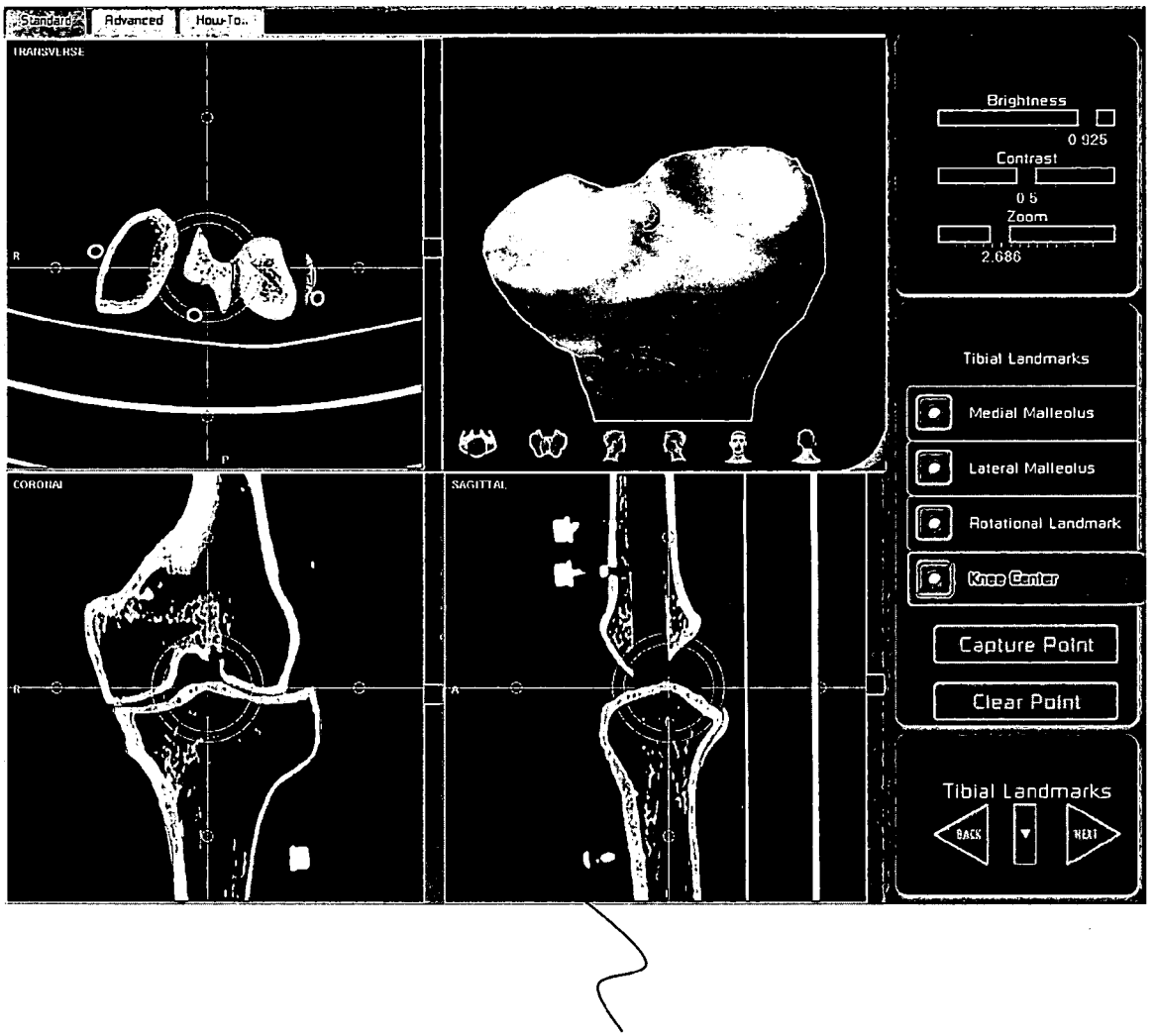

183
Standard
Advanced
How-To..
Brightness
0.925
Contrast
0.5
Zoom
2.686
Tibial Landmarks
Medial Malleolus
Lateral Malleolus
Rotational Landmark
Knee Center
Capture Point
Clear Point
Tibial Landmarks
BACK
NEXT
CORONAL
SAGITTAL
R
A
83c

FIG. 22


Standard
Advanced
How-To..
TRANSVERSE
R
P
CORONAL
R
SAGITTAL
A
Brightness
0.925
Contrast
0.5
Zoom
2.686
Tibial Landmarks
Medial Malleolus
Lateral Malleolus
Rotational Landmark
Knee Center
Capture Point
Clear Point
Tibial Landmarks
BACK
NEXT

83d

FIG. 23

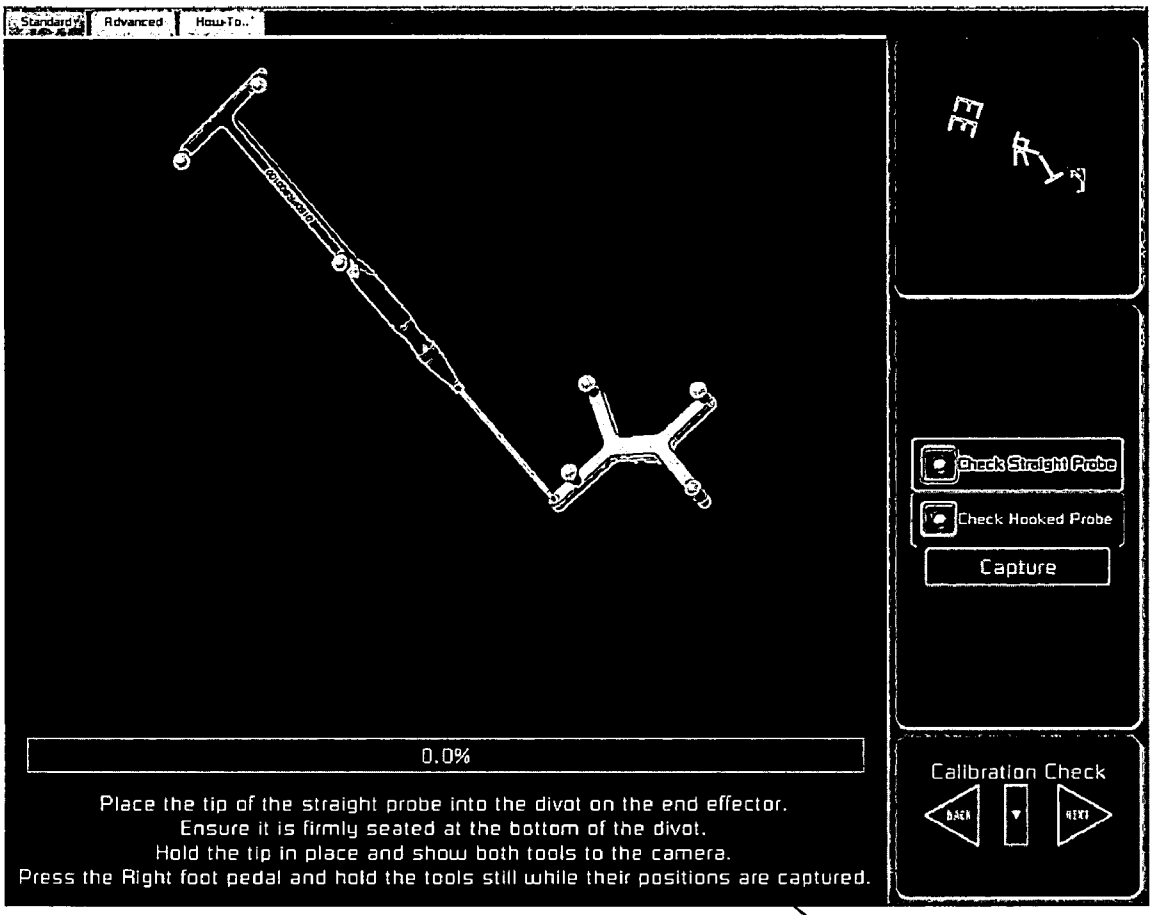

Standard
Advanced
How-To..
Check Straight Probe
Check Hooked Probe
Capture
0.0%
Calibration Check
Place the tip of the straight probe into the divot on the end effector.
Ensure it is firmly seated at the bottom of the divot.
Hold the tip in place and show both tools to the camera.
Press the Right foot pedal and hold the tools still while their positions are captured.
84

FIG. 24

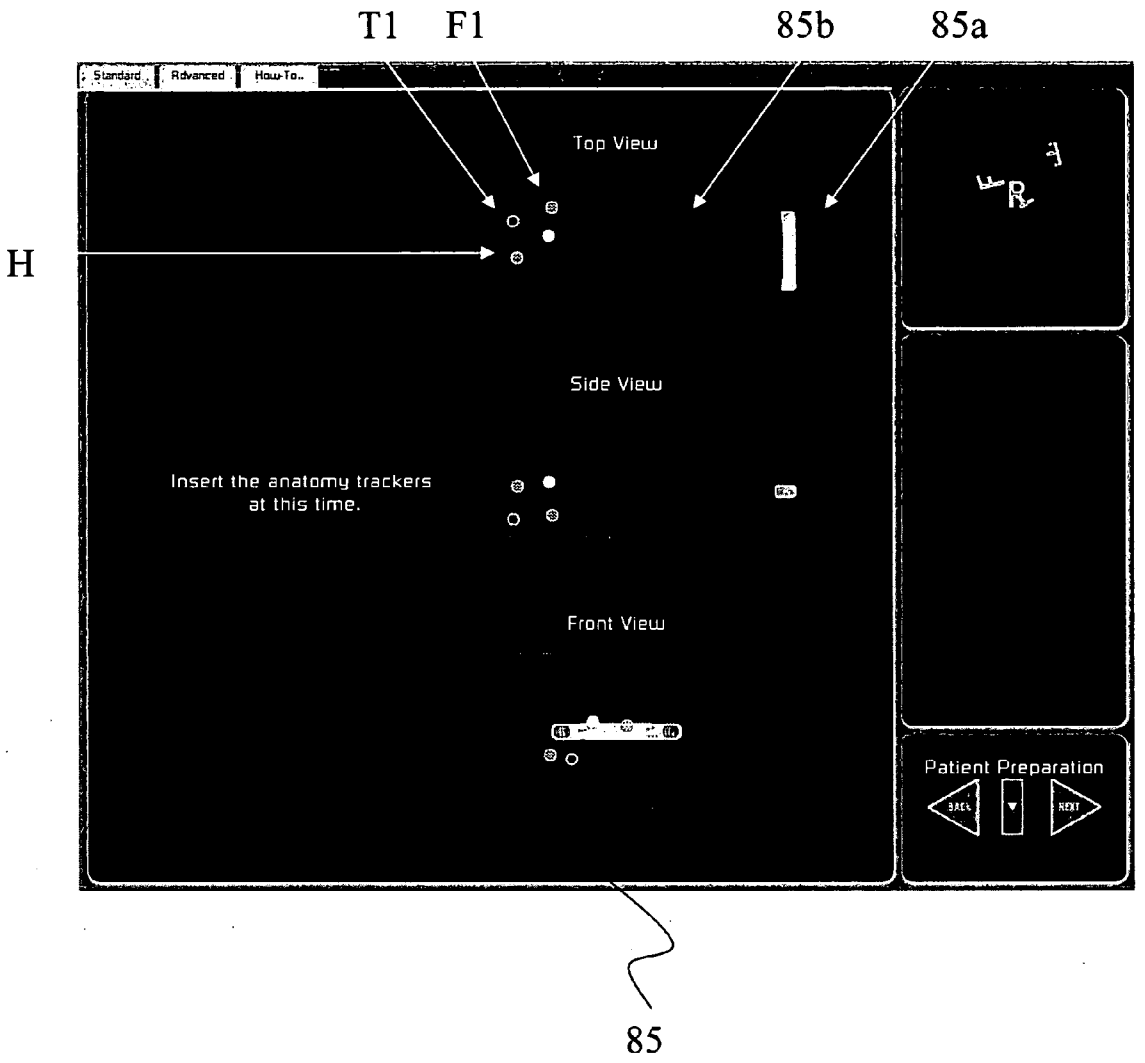
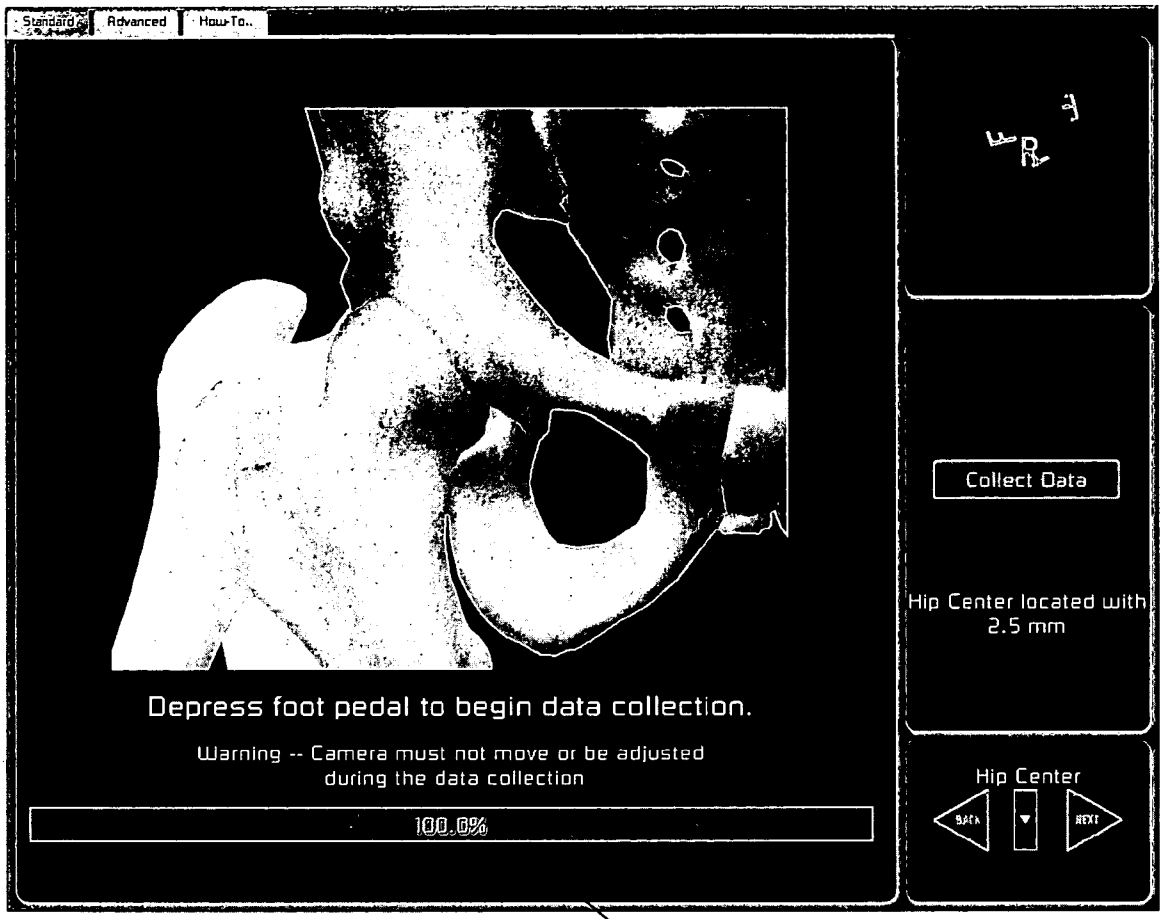
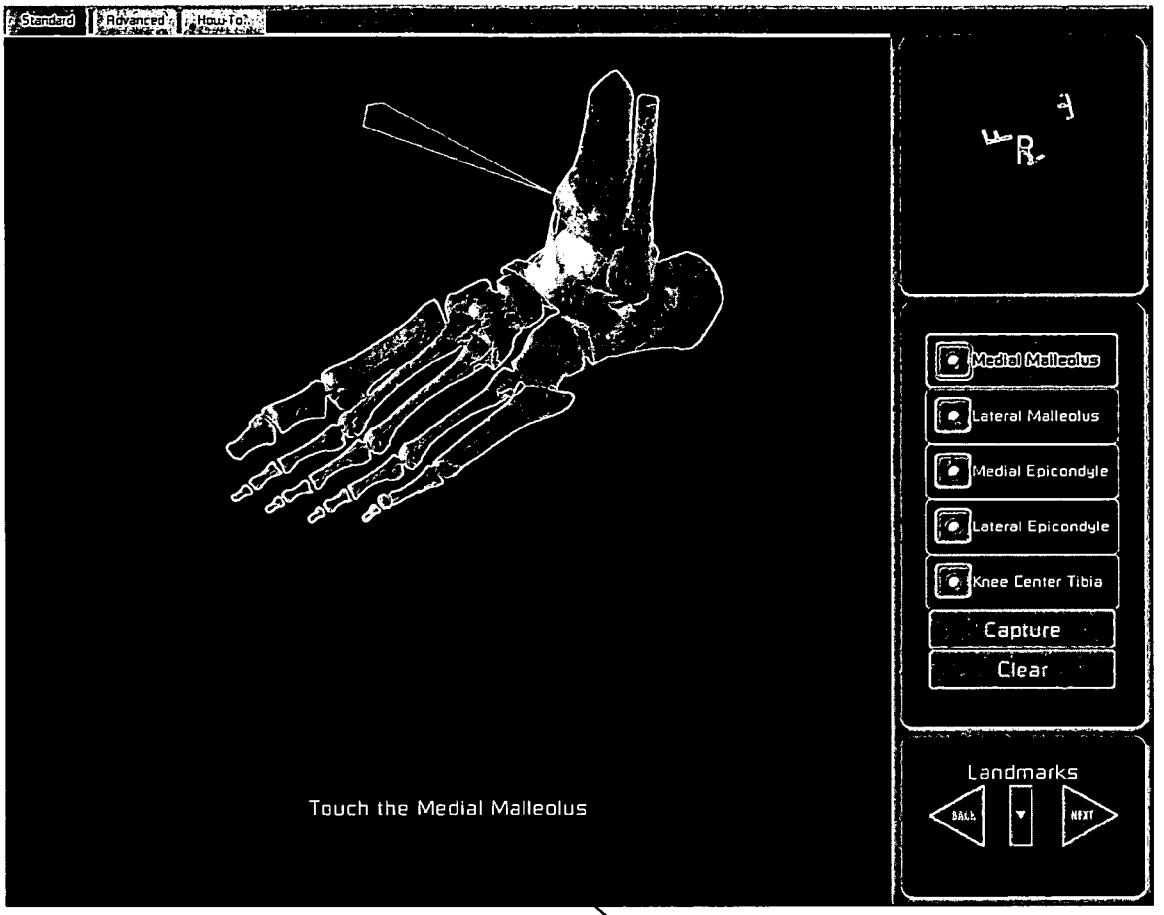

T1
F1
85b
85a
H
Standard
Advanced
How-To..
Top View
Side View
Insert the anatomy trackers at this time.
Front View
Patient Preparation
BACK
NEXT
85

FIG. 25


Standard
Advanced
How-To..
Collect Data
Hip Center located with 2.5 mm
Depress foot pedal to begin data collection.
Warning -- Camera must not move or be adjusted during the data collection
100.0%
Hip Center
BACK
NEXT

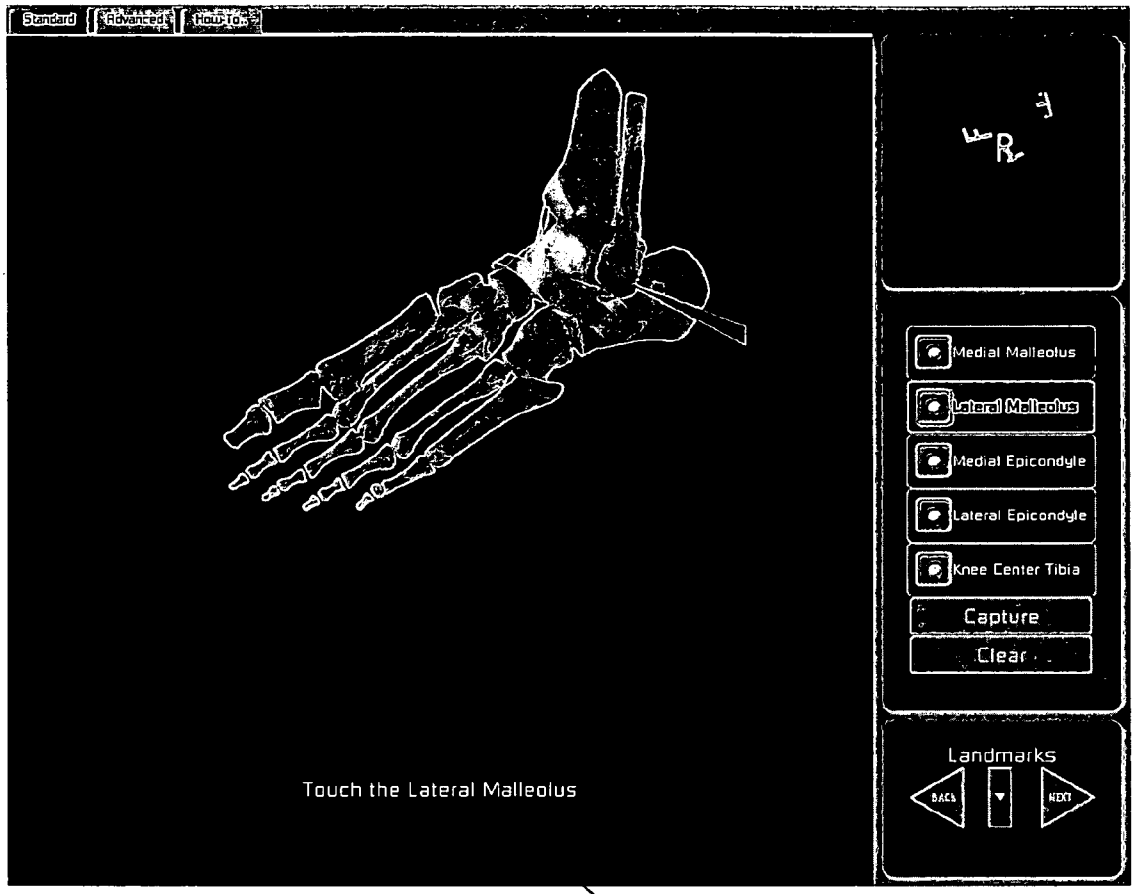
86a

FIG. 26


Standard
Advanced
How-To
Medial Malleolus
Lateral Malleolus
Medial Epicondyle
Lateral Epicondyle
Knee Center Tibia
Capture
Clear
Landmarks
BACK
NEXT
Touch the Medial Malleolus

86b

FIG. 27


Standard
Advanced
How To...
Medial Malleolus
Lateral Malleolus
Medial Epicondyle
Lateral Epicondyle
Knee Center Tibia
Capture
Clear
Landmarks
BACK
NEXT
Touch the Lateral Malleolus

86c

FIG. 28

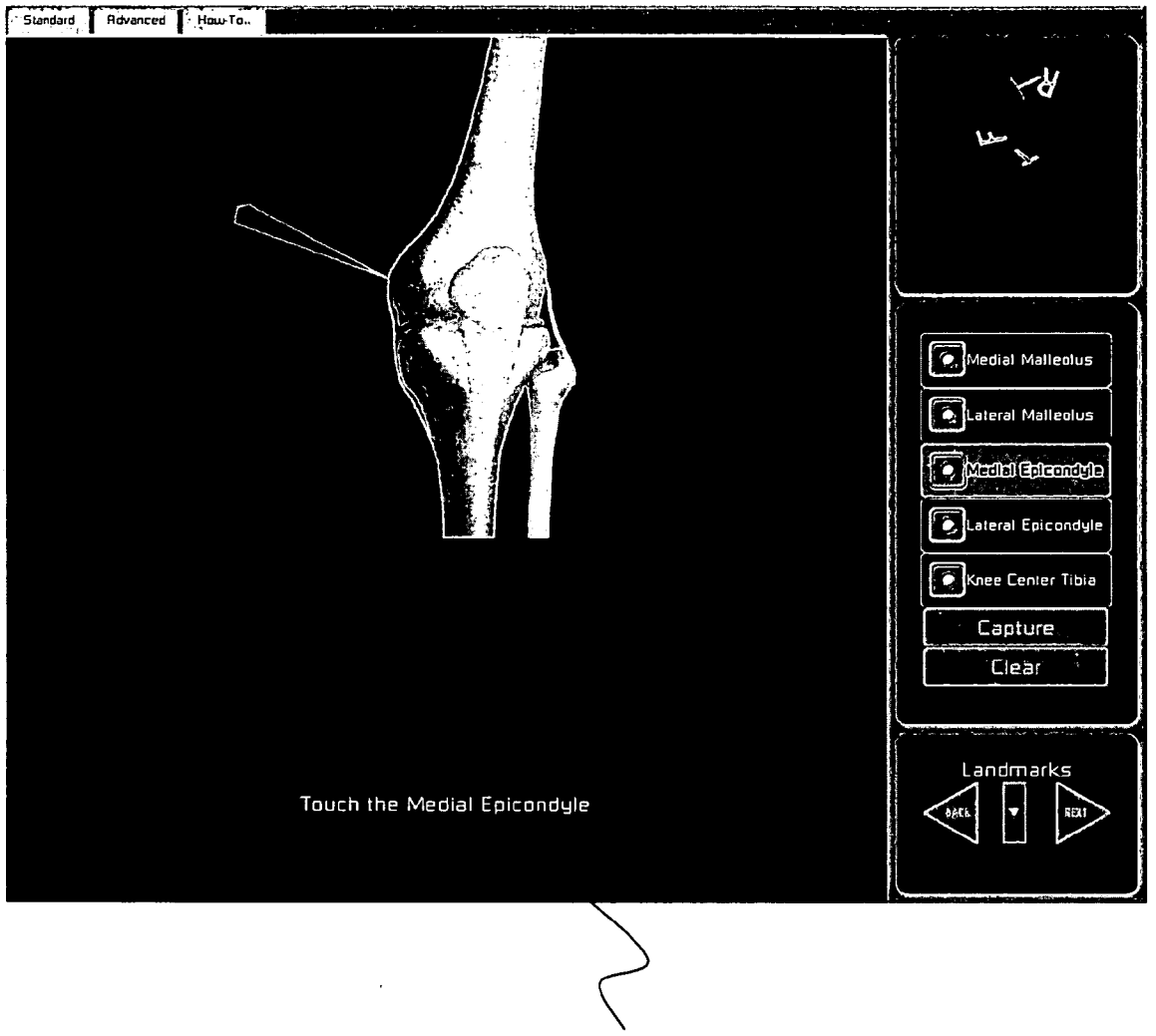

Standard
Advanced
How-To..
Medial Malleolus
Lateral Malleolus
Medial Epicondyle
Lateral Epicondyle
Knee Center Tibia
Capture
Clear
Landmarks
Touch the Medial Epicondyle
86d

FIG. 29

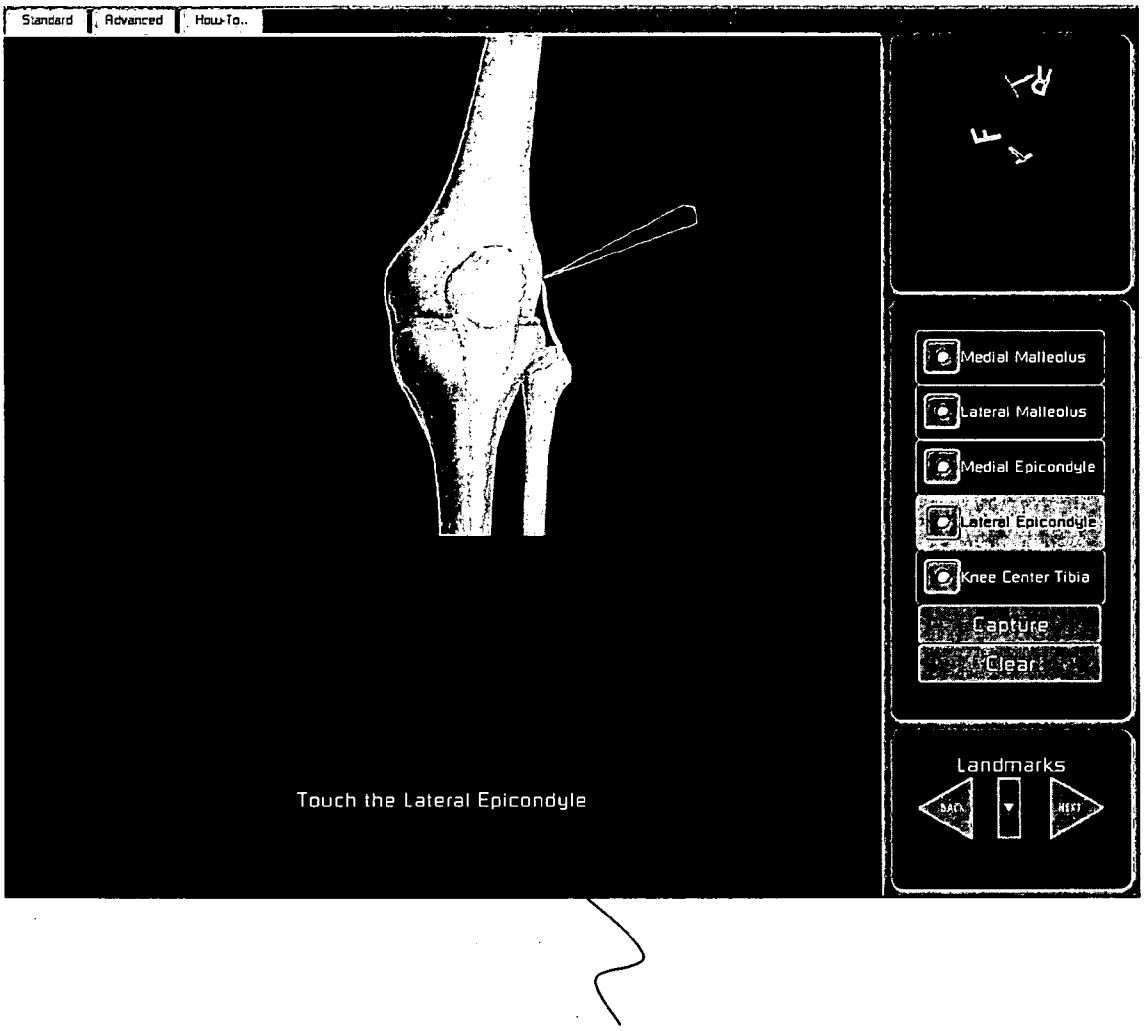
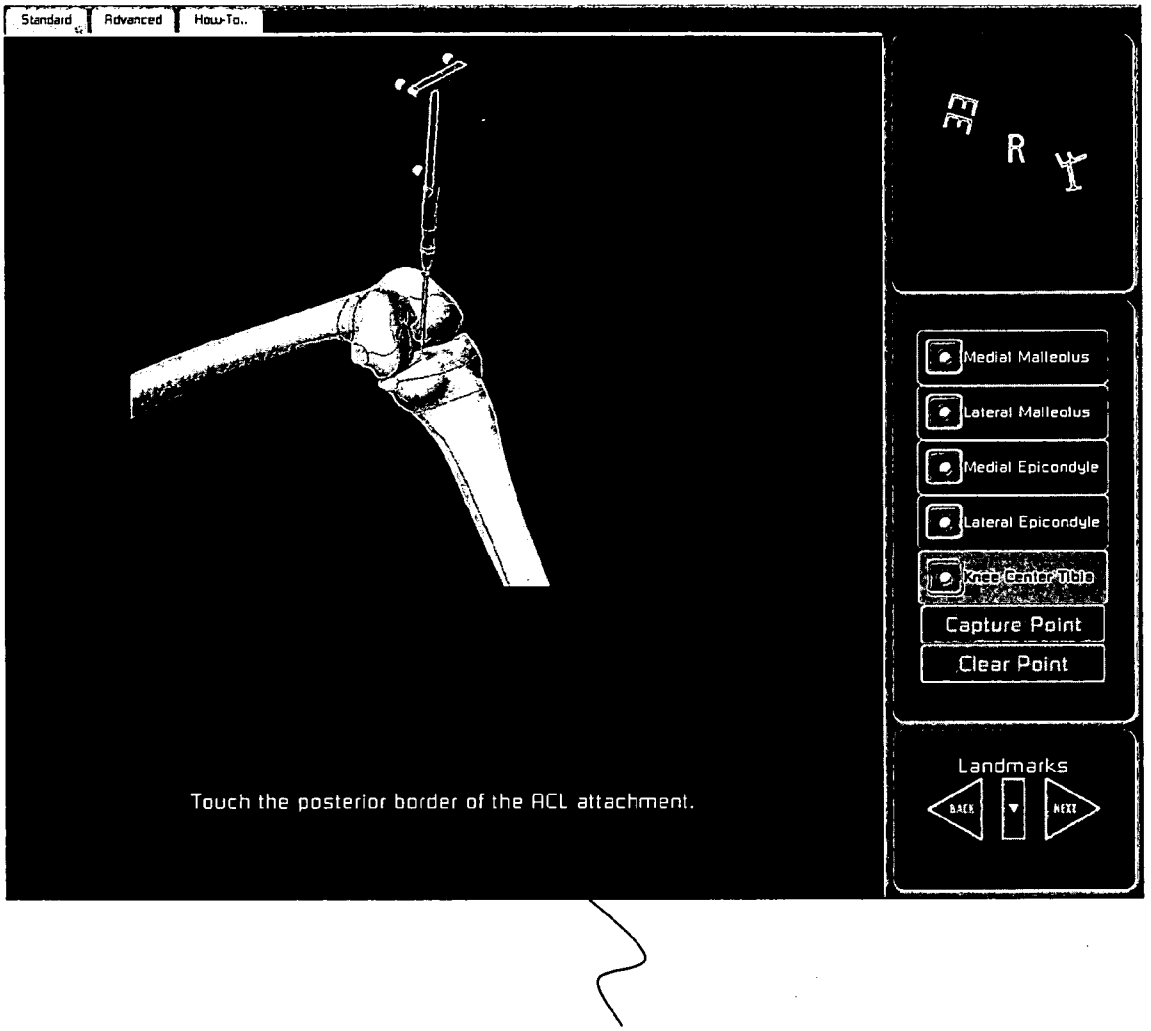

Standard
Advanced
How-To..
Medial Malleolus
Lateral Malleolus
Medial Epicondyle
Lateral Epicondyle
Knee Center Tibia
Capture
Clear
Landmarks
BACK
NEXT
Touch the Lateral Epicondyle
86e

FIG. 30


Standard
Advanced
How-To..
Medial Malleolus
Lateral Malleolus
Medial Epicondyle
Lateral Epicondyle
Knee Center Tibia
Capture Point
Clear Point
Landmarks
BACK
NEXT
Touch the posterior border of the ACL attachment.

86f

FIG. 31

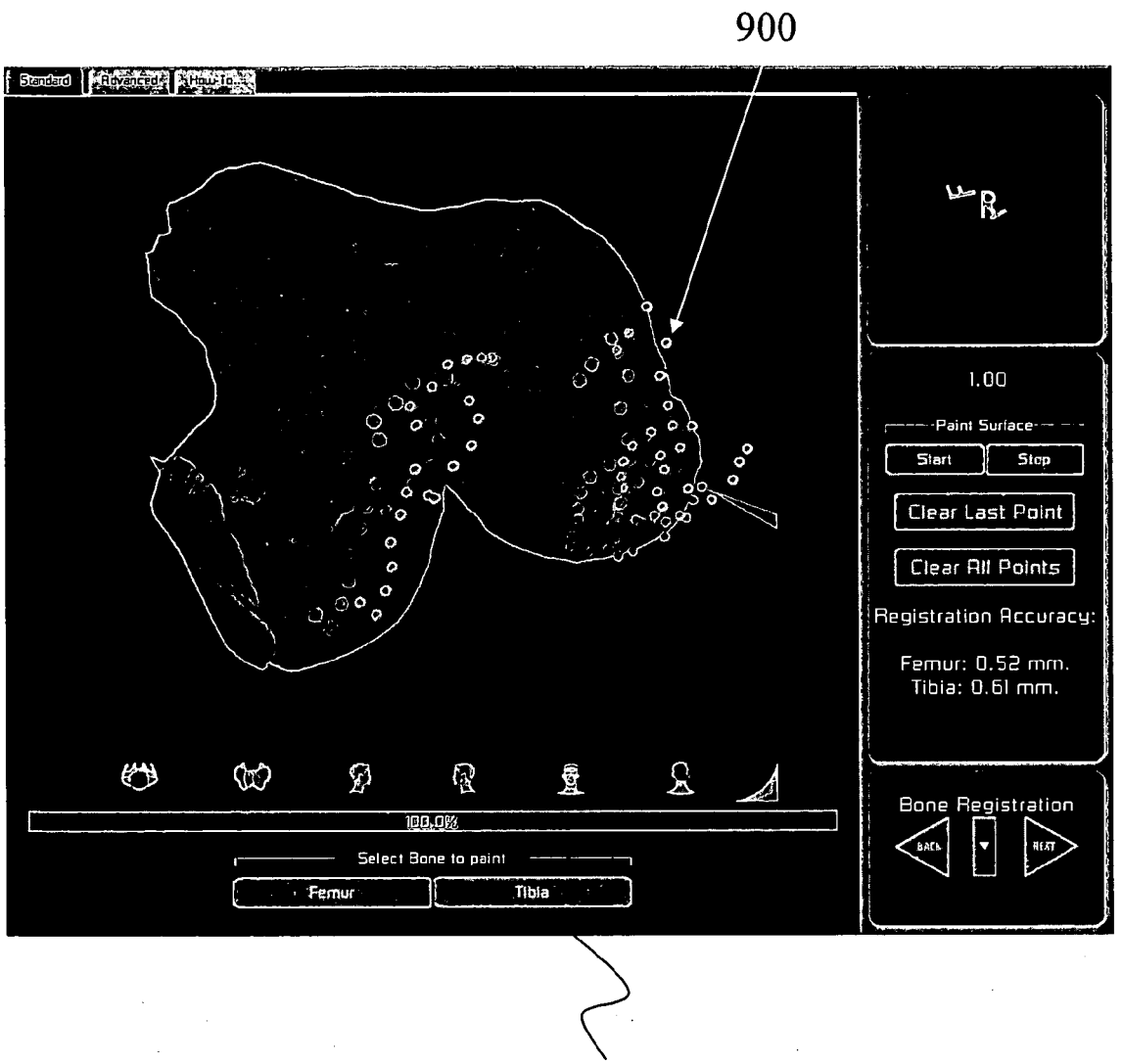

900
Standard
Advanced
How To...
1.00
Paint Surface
Start
Stop
Clear Last Point
Clear All Points
Registration Accuracy:
Femur: 0.52 mm.
Tibia: 0.61 mm.
100.0%
Select Bone to paint
Femur
Tibia
Bone Registration
BACK
NEXT
86g

FIG. 32

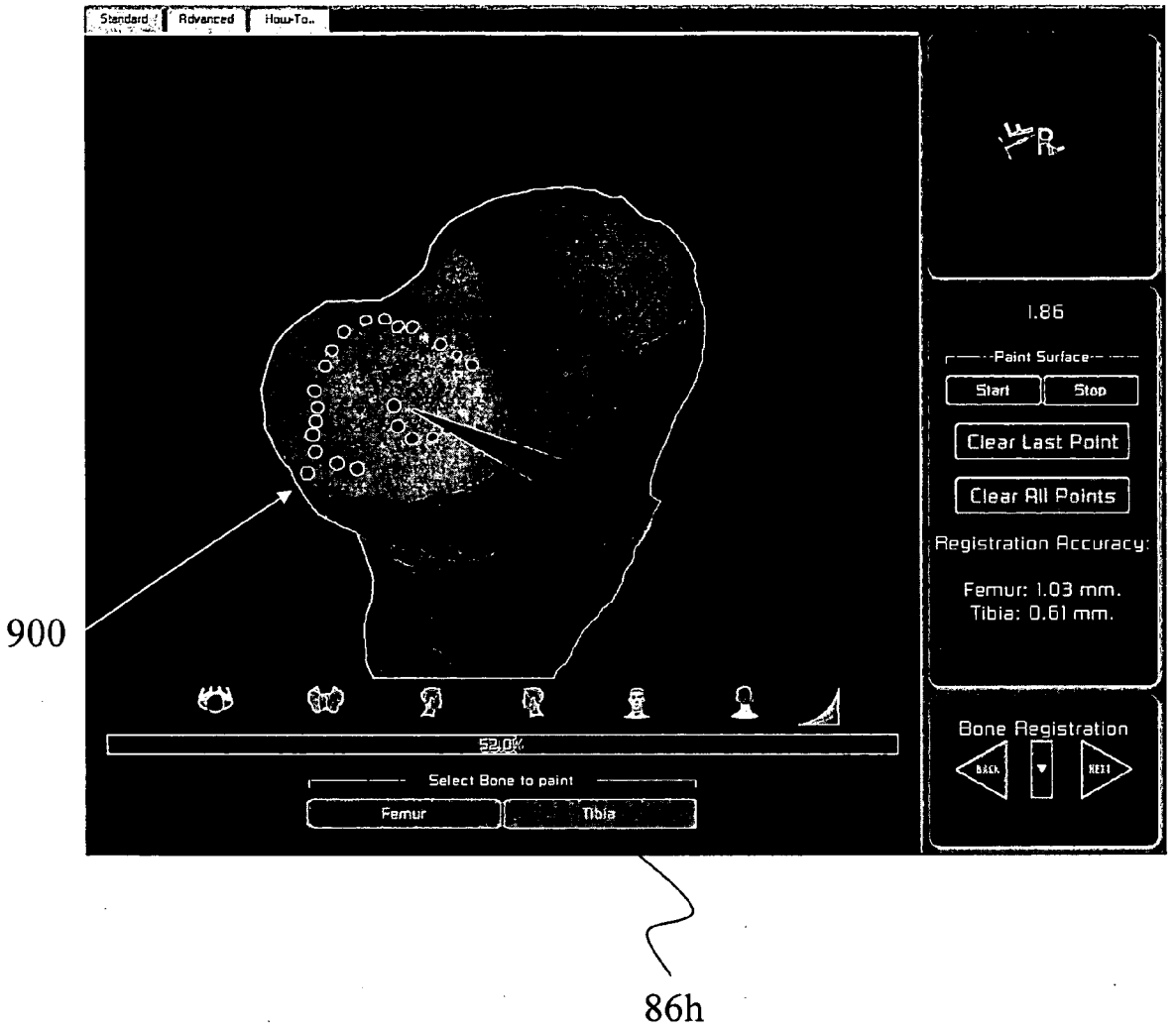

Standard
Advanced
How-To..
1.86
Paint Surface
Start
Stop
Clear Last Point
Clear All Points
Registration Accuracy:
Femur: 1.03 mm.
Tibia: 0.61 mm.
Bone Registration
BACK
NEXT
52.0%
Select Bone to paint
Femur
Tibia
900
86h

FIG. 33

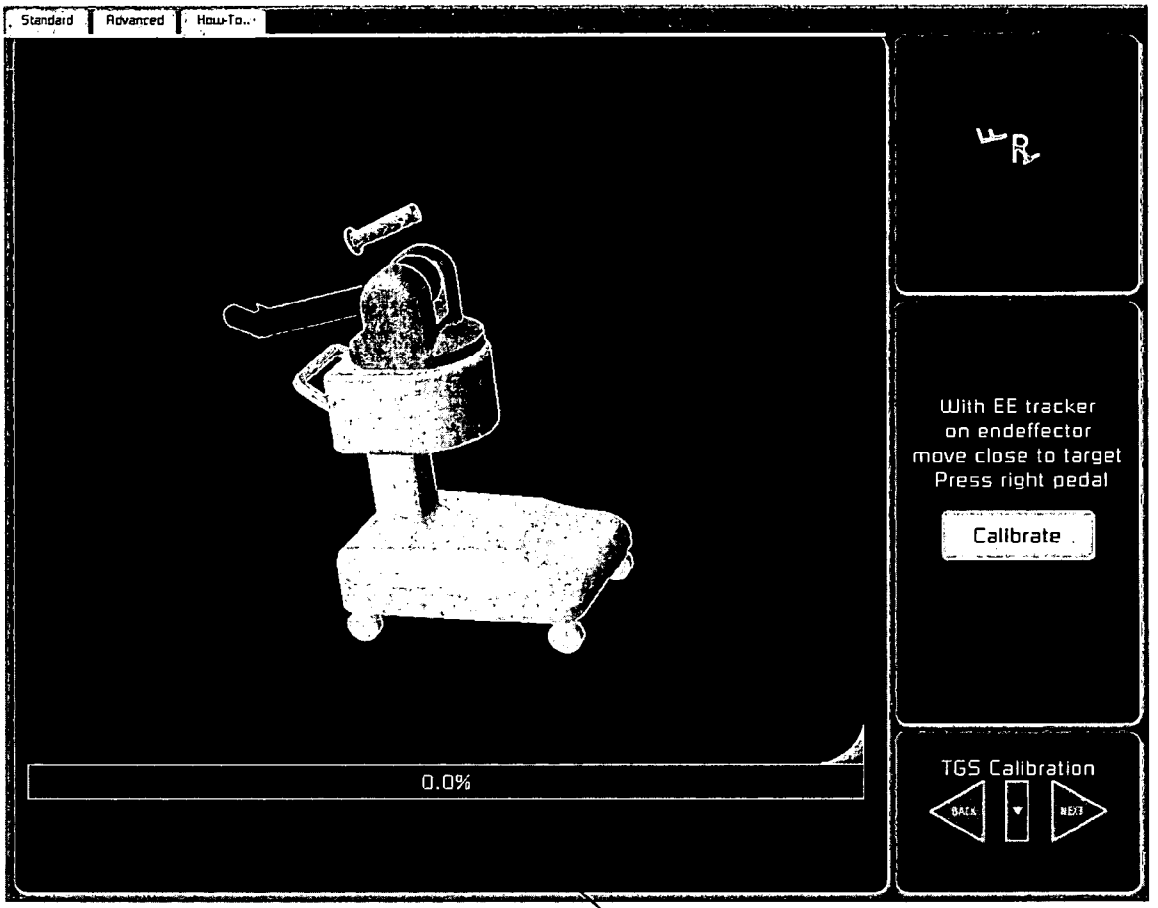

Standard
Advanced
How-To...
With EE tracker
on endeffector
move close to target
Press right pedal
Calibrate
0.0%
TGS Calibration
BACK
NEXT
87

FIG. 34

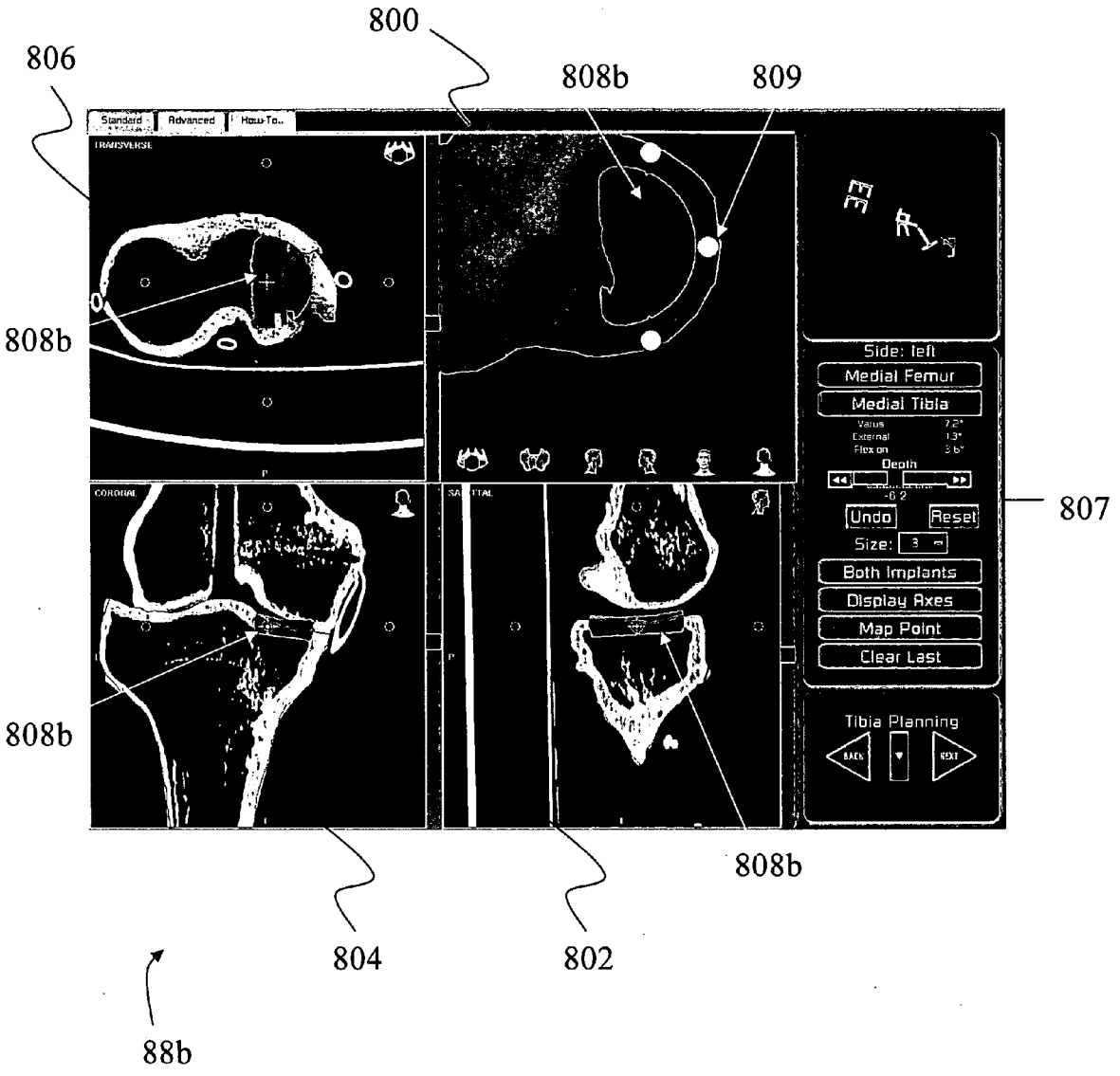

800
806
808b
809
808b
807
808b
808b
804
802
88b
Standard
Advanced
How-To...
TRANSVERSE
CORONAL
SAGITTAL
Side: left
Medial Femur
Medial Tibia
Depth
Undo
Reset
Size:
Both Implants
Display Axes
Map Point
Clear Last
Tibia Planning
BACK
NEXT

FIG. 35

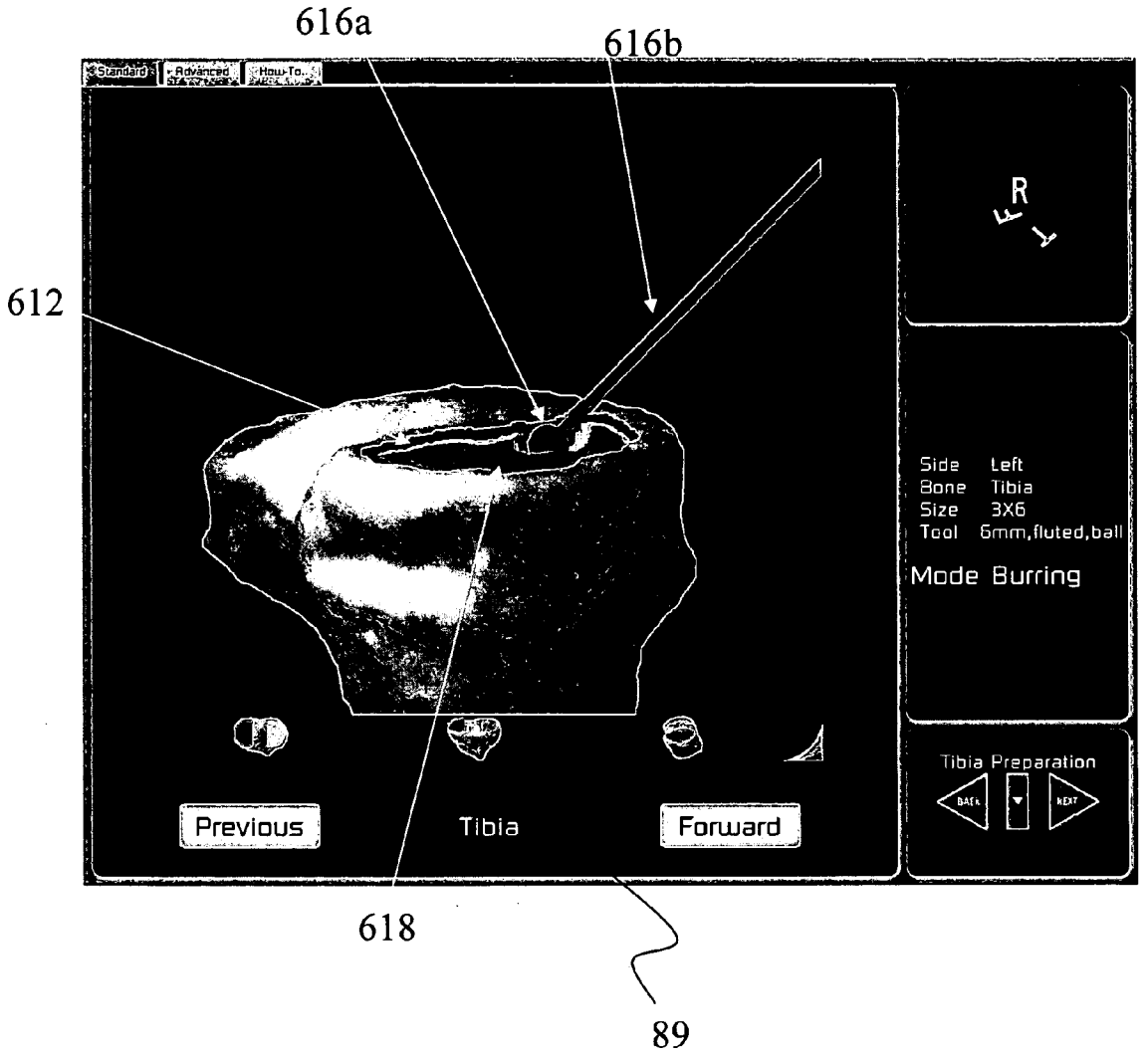

616a
616b
612
Standard
Advanced
How-To..
R
Side Left
Bone Tibia
Size 3X6
Tool 6mm,fluted,ball
Mode Burring
Tibia Preparation
BACK
NEXT
Previous
Tibia
Forward
618
89

FIG. 36

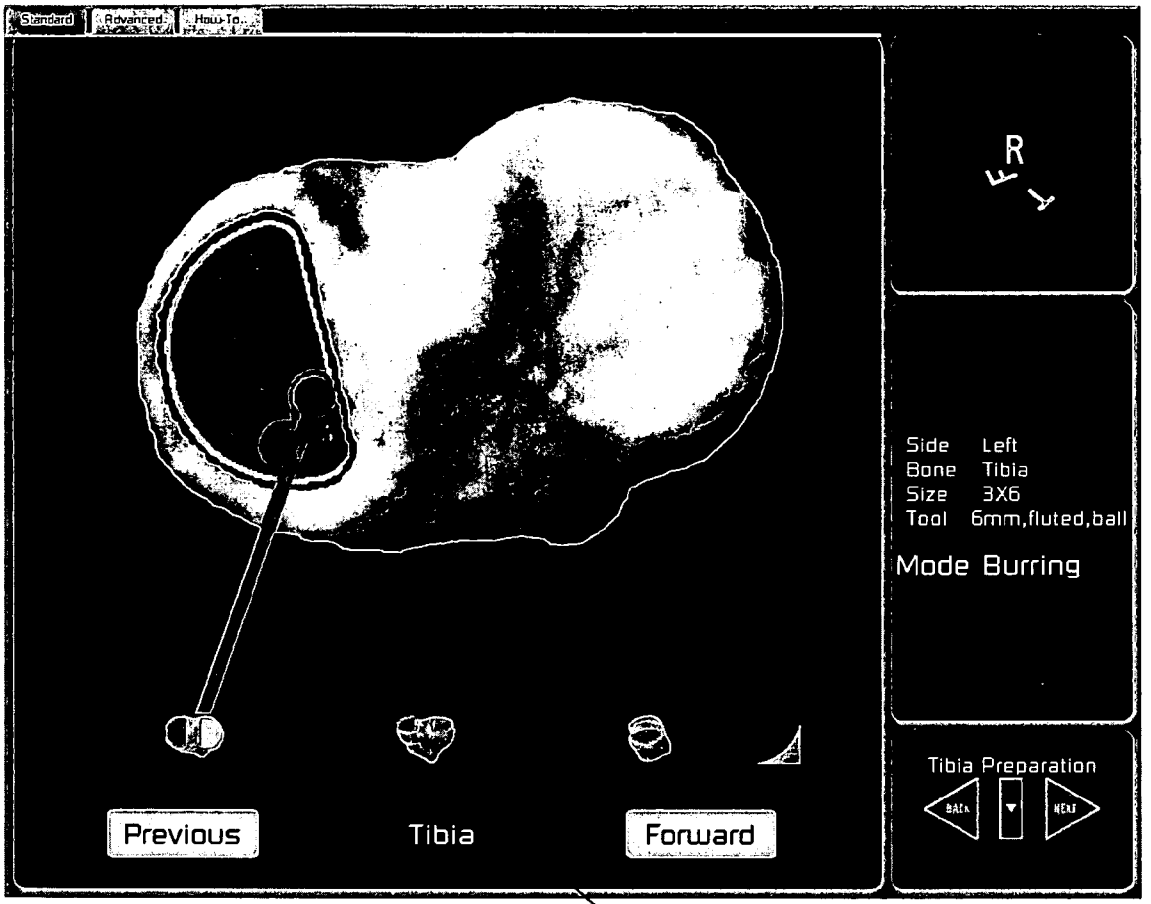

Standard
Advanced
How-To..
F
R
T
Side Left
Bone Tibia
Size 3X6
Tool 6mm,fluted,ball
Mode Burring
Tibia Preparation
Previous
Tibia
Forward
89

FIG. 37

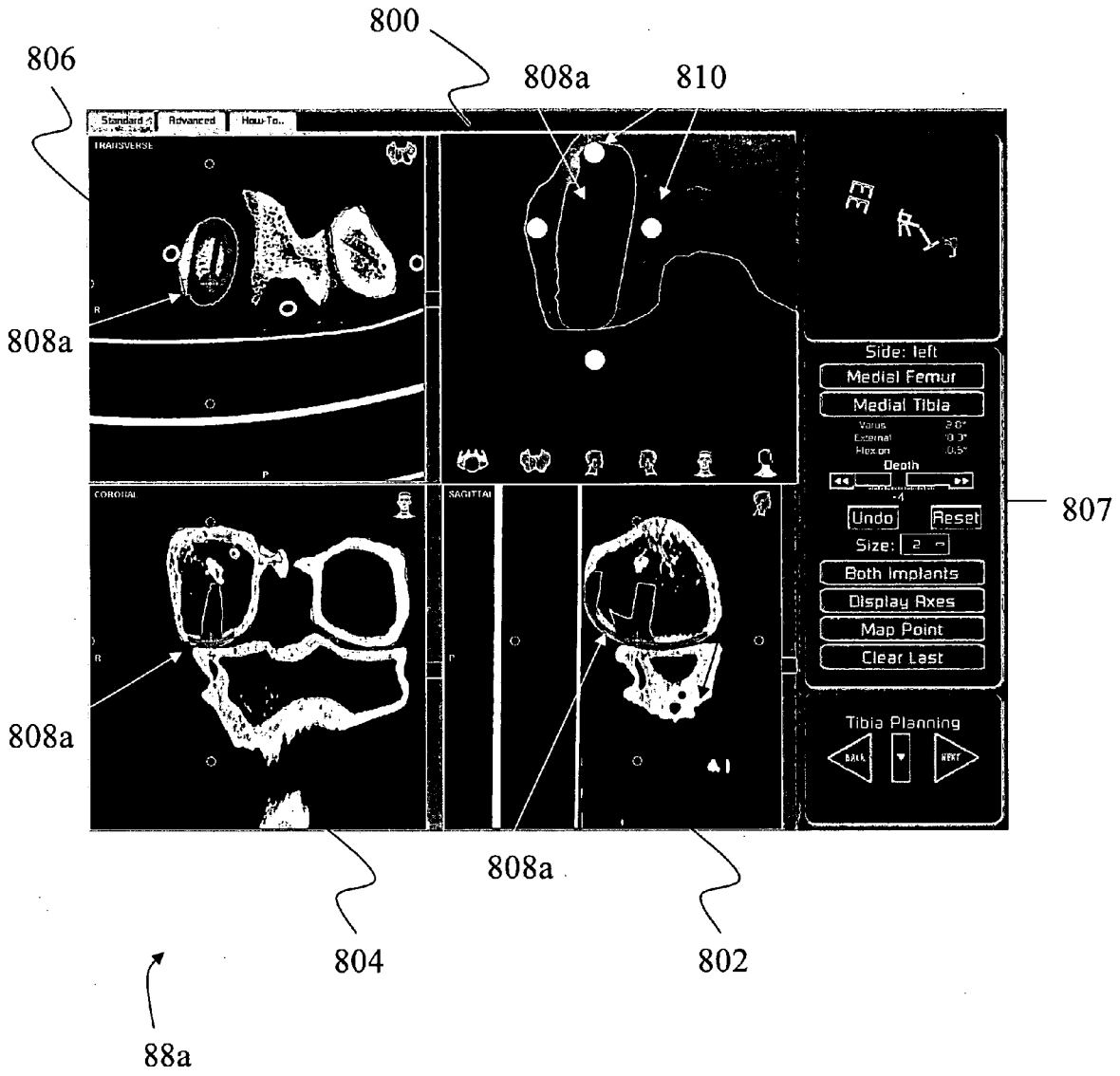

800
806
808a
810
808a
807
808a
808a
804
802
88a
Standard
Advanced
How-To..
TRANSVERSE
CORONAL
SAGITTAL
Side: left
Medial Femur
Medial Tibia
Depth
Undo
Reset
Size:
Both Implants
Display Axes
Map Point
Clear Last
Tibia Planning
BACK
NEXT

FIG. 38

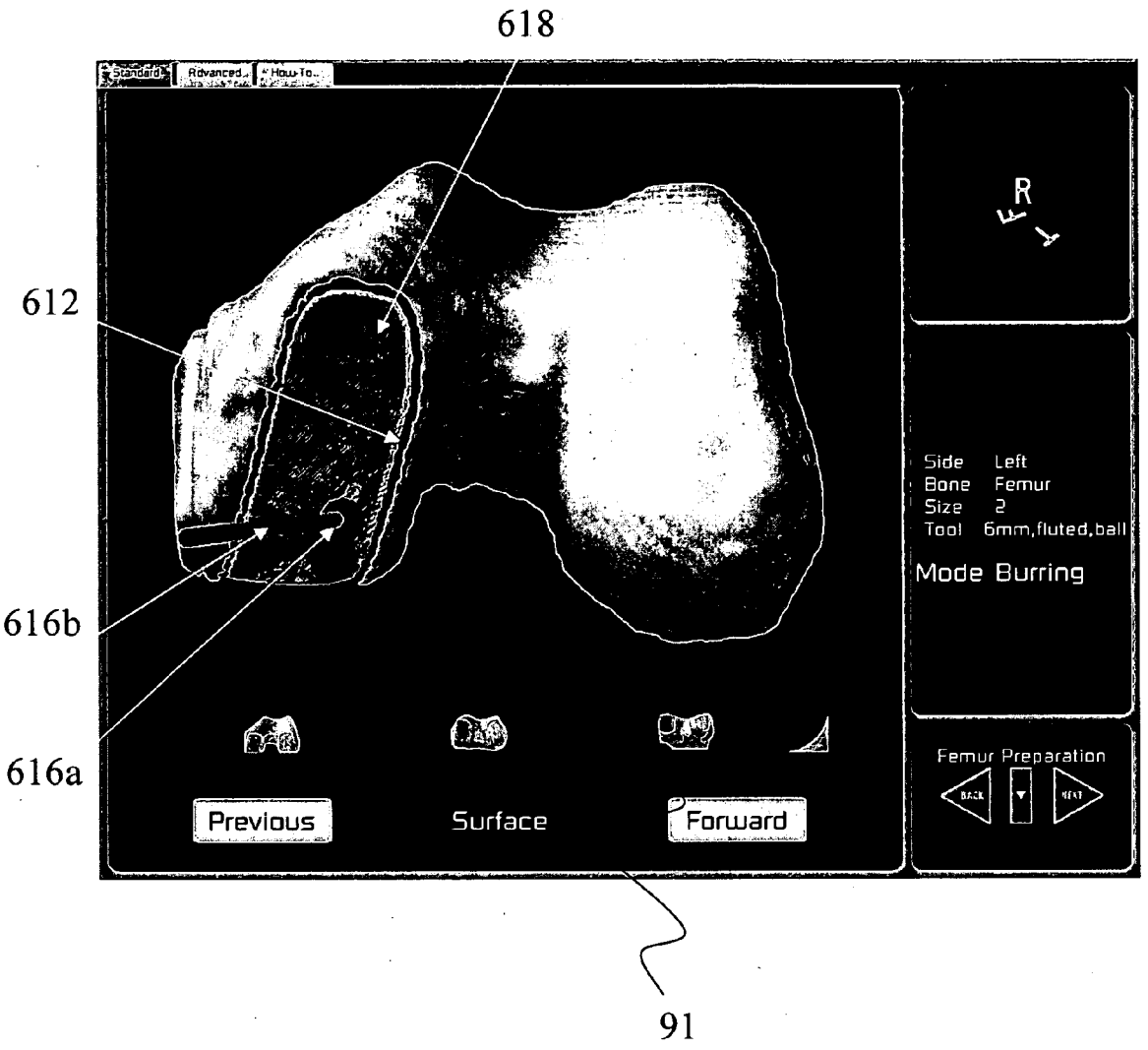

618
612
616b
616a
91
Standard
Advanced
How-To
Side Left
Bone Femur
Size 2
Tool 6mm,fluted,ball
Mode Burring
Femur Preparation
BACK
NEXT
Previous
Surface
Forward

FIG. 39

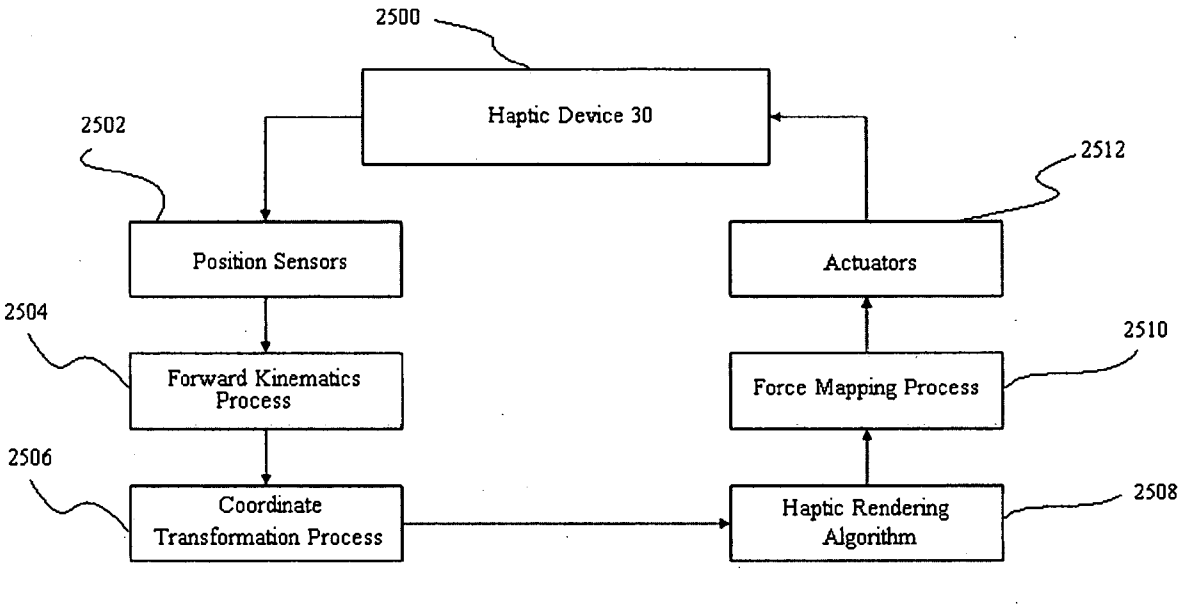

2500
Haptic Device 30
2502
2512
Position Sensors
Actuators
2504
2510
Forward Kinematics Process
Force Mapping Process
2506
2508
Coordinate Transformation Process
Haptic Rendering Algorithm

FIG. 40

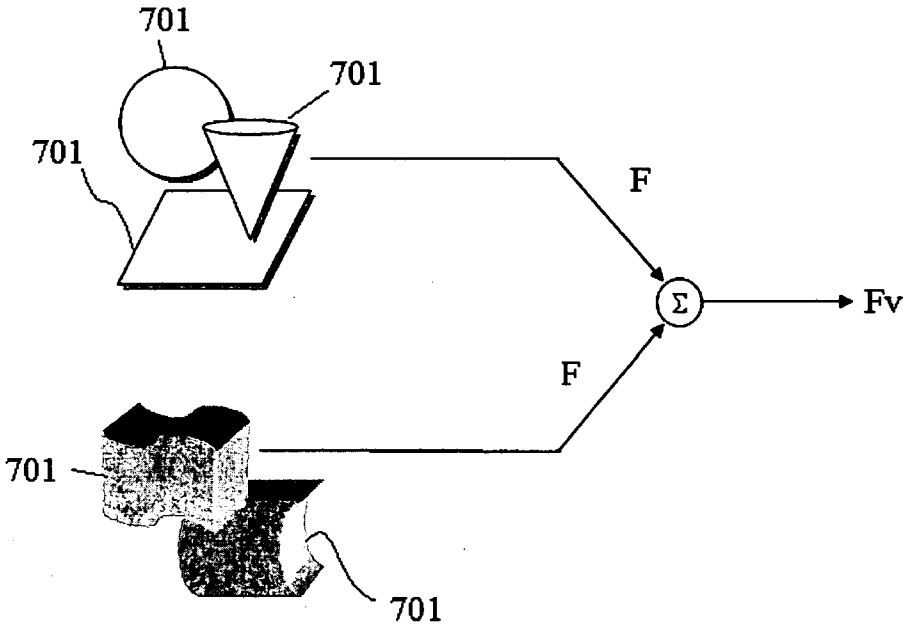


FIG. 41

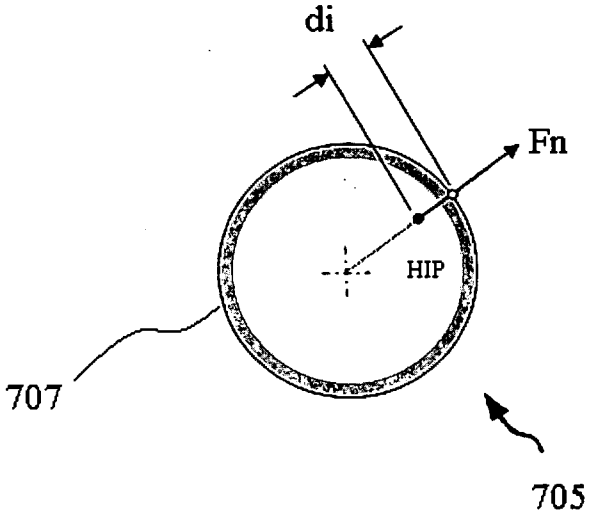


FIG. 42

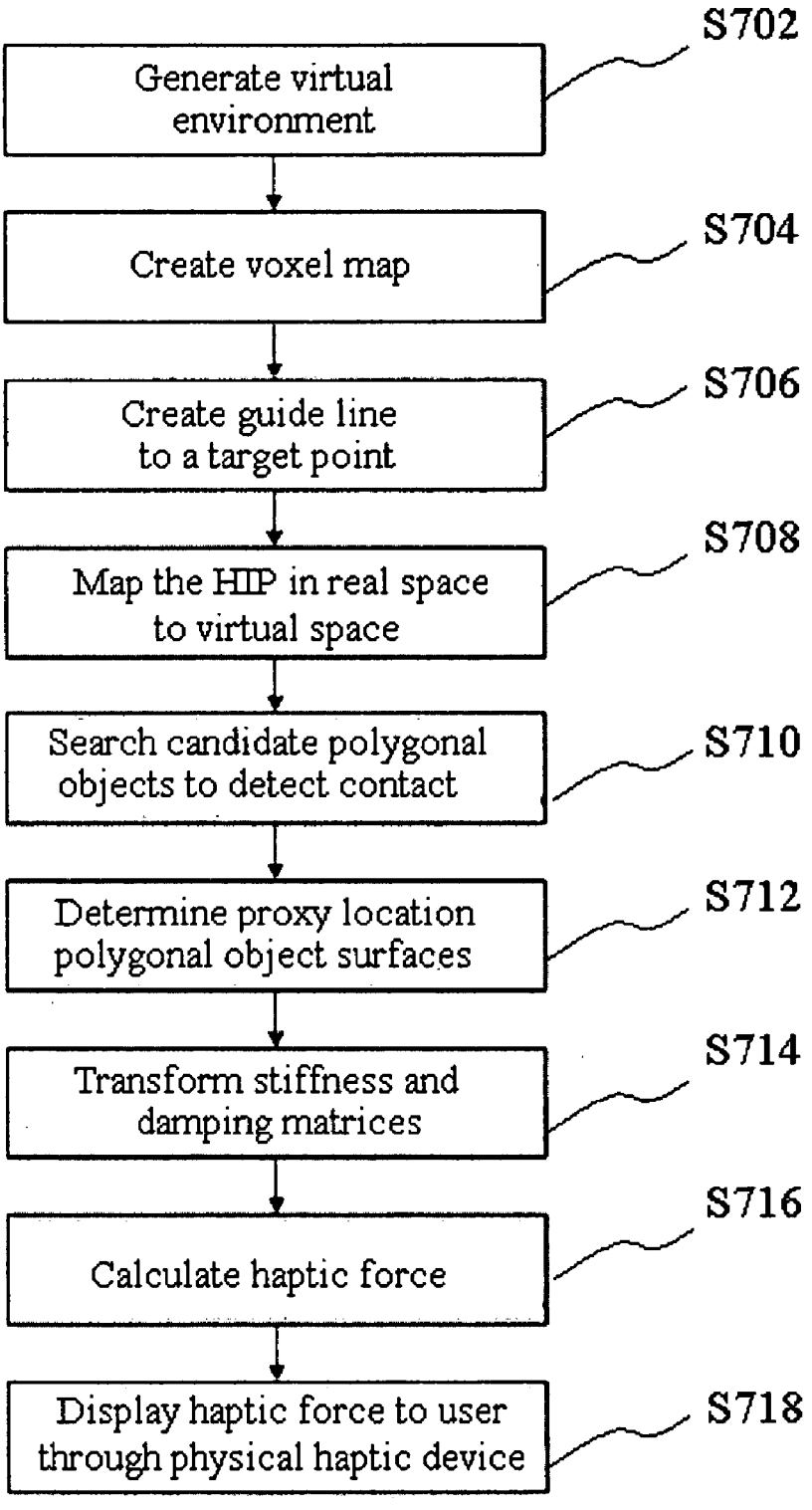

S702
Generate virtual environment
S704
Create voxel map
S706
Create guide line to a target point
S708
Map the HIP in real space to virtual space
S710
Search candidate polygonal objects to detect contact
S712
Determine proxy location polygonal object surfaces
S714
Transform stiffness and damping matrices
S716
Calculate haptic force
S718
Display haptic force to user through physical haptic device

FIG. 43

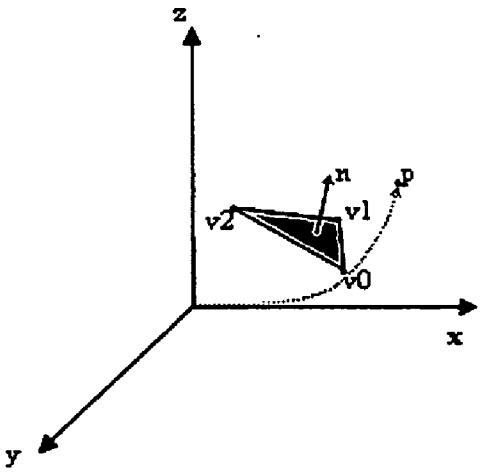


FIG. 44

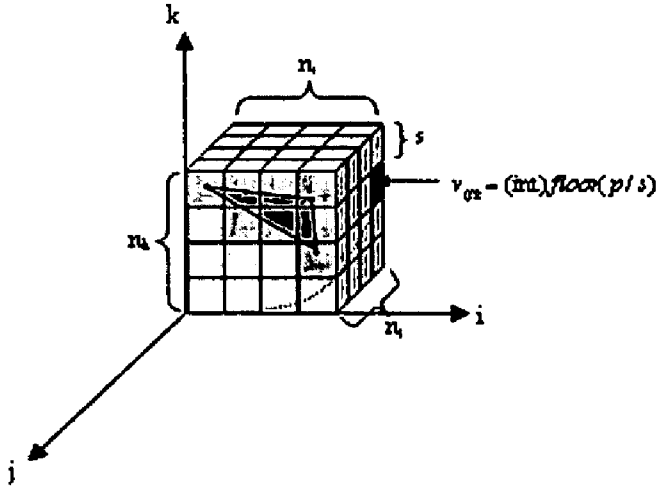


FIG. 45

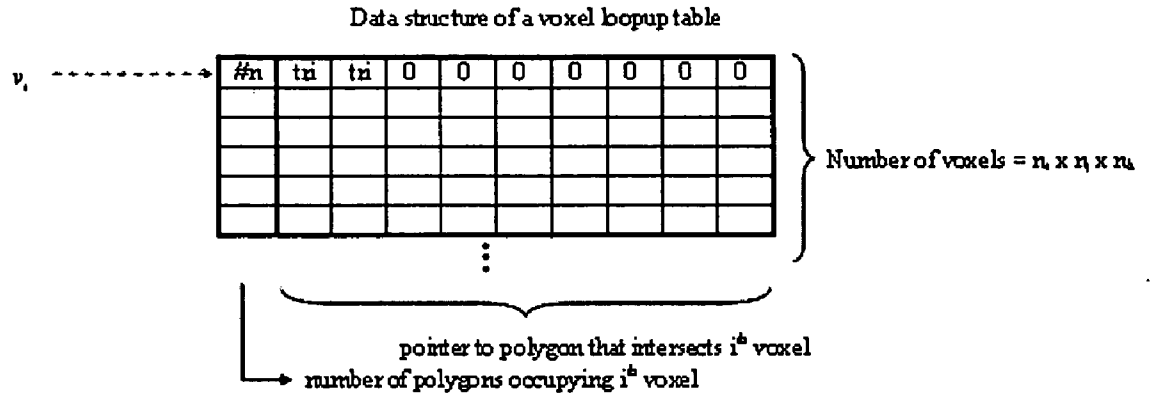


FIG. 46A

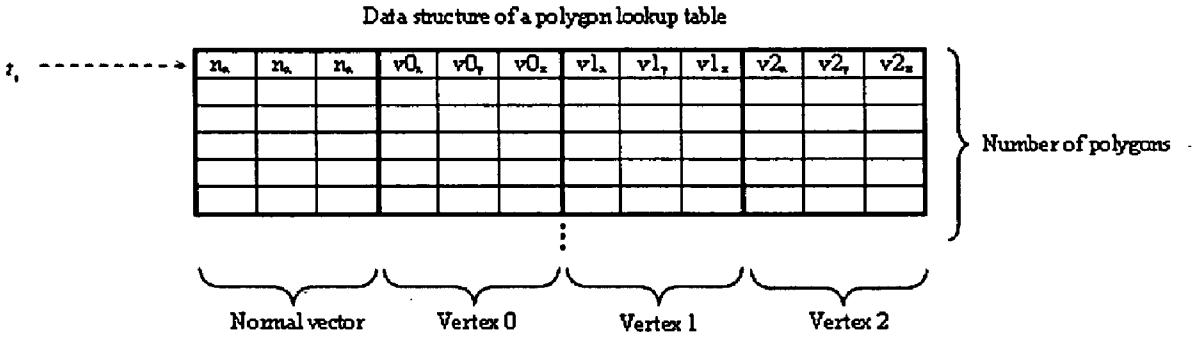


FIG. 46B

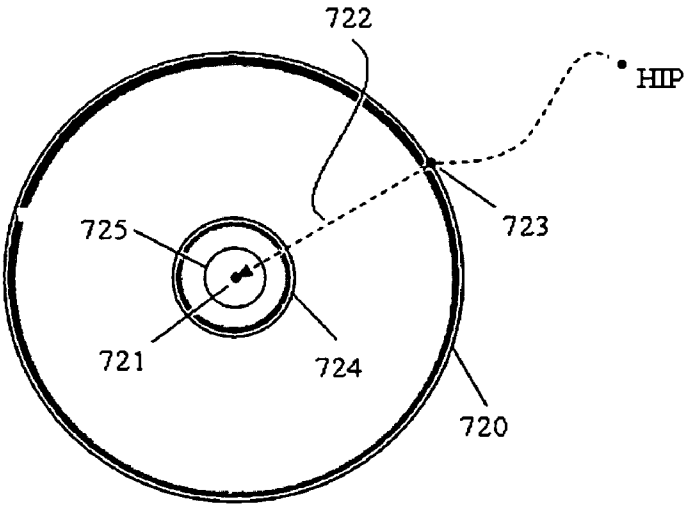


FIG. 47

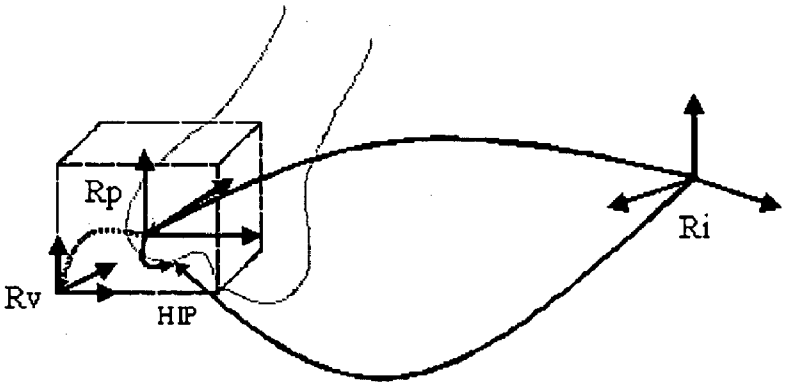


FIG. 48

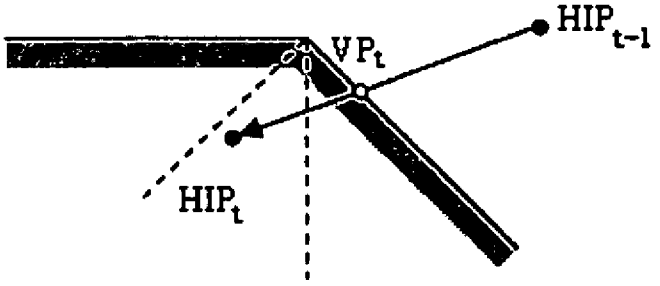


FIG. 49A

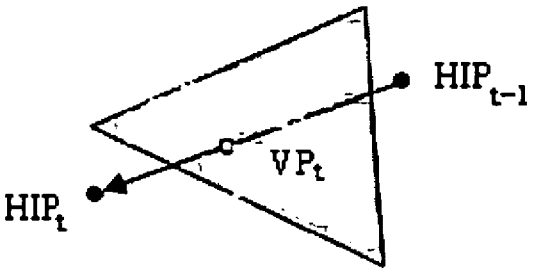


FIG. 49B

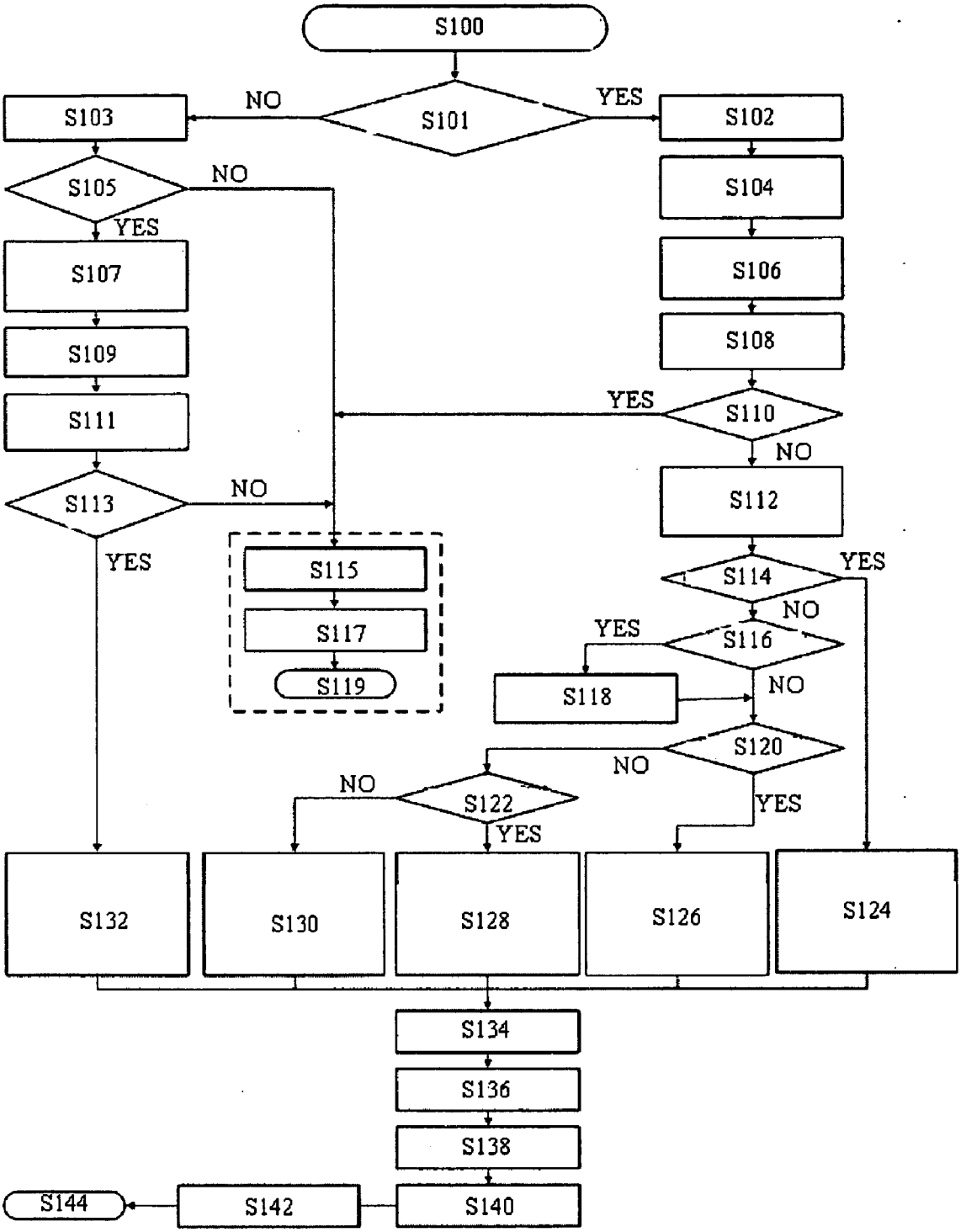

S100
S101
NO
YES
S103
S102
S105
NO
S104
YES
S107
S106
S109
S108
S111
YES
S110
NO
S113
NO
S112
YES
S115
S114
YES
NO
S117
YES
S116
S119
S118
NO
S120
NO
NO
S122
YES
YES
S132
S130
S128
S126
S124
S134
S136
S138
S144
S142
S140

FIG. 50

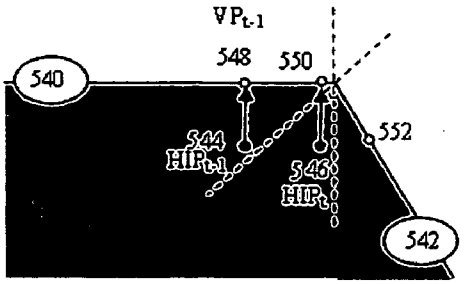


FIG. 51A

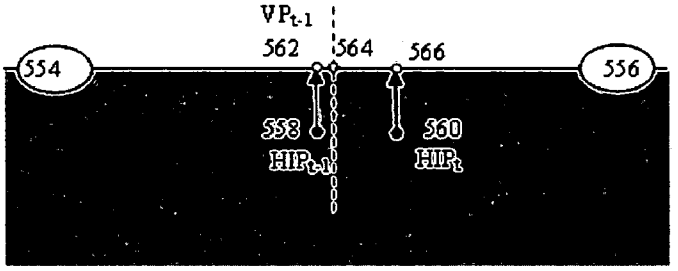


FIG. 51B

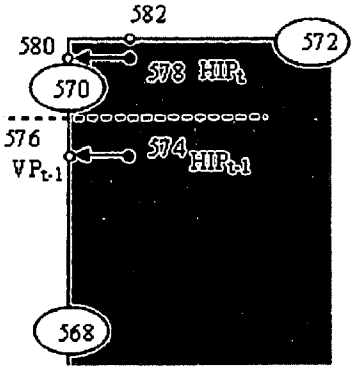


FIG. 51C

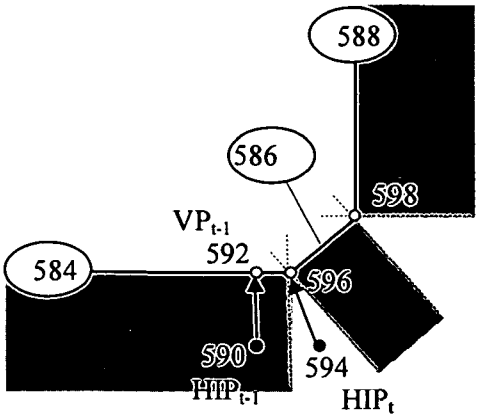


FIG. 51D

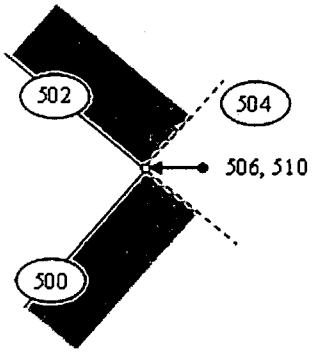


FIG. 52A

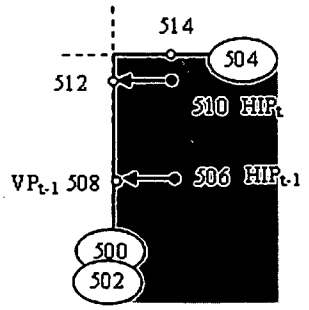


FIG. 52B

HAPTIC GUIDANCE SYSTEM AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. patent application Ser. No. 10/384,072, filed Mar. 6, 2003, published Feb. 5, 2004; U.S. patent application Ser. No. 10/384,077, filed Mar. 6, 2003, published Feb. 19, 2004; and U.S. patent application Ser. No. 10/384,194, filed Mar. 6, 2003, published Feb. 19, 2004, each of which claims priority from U.S. Provisional Patent Application No. 60/362,368, filed Mar. 6, 2002. This application is also a continuation-in-part of U.S. patent application Ser. No. 10/621,119, filed Jul. 16, 2003, published Jun. 3, 2004, which is a continuation-in-part of U.S. patent application Ser. No. 10/384,078, filed Mar. 6, 2003, published Feb. 19, 2004, which claims priority from U.S. Provisional Patent Application Ser. No. 60/362,368, filed Mar. 6, 2002. This application further claims priority from U.S. Provisional Patent Application Ser. No. 60/655,642, filed Feb. 22, 2005, and U.S. Provisional Patent Application Ser. No. 60/759,186, filed Jan. 17, 2006. Each of the above-referenced published applications is incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The invention relates to a surgical system and, more particularly, to a surgical system and method for orthopedic joint replacement.

[0004] 2. Description of Related Art

[0005] Minimally invasive surgery (MIS) is the performance of surgery through incisions that are considerably smaller than incisions used in traditional surgical approaches. For example, in an orthopedic application such as total knee replacement surgery, an MIS incision length may be in a range of about 4 to 6 inches whereas an incision length in traditional total knee surgery is typically in a range of about 6 to 12 inches. As a result of the smaller incision length, MIS procedures are generally less invasive than traditional surgical approaches, which minimizes trauma to soft tissue, reduces post-operative pain, promotes earlier mobilization, shortens hospital stays, and speeds rehabilitation.

[0006] One drawback of MIS is that the small incision size reduces a surgeon's ability to view and access the anatomy. For example, in minimally invasive orthopedic joint replacement, limited visibility and limited access to the joint increase the complexity of assessing proper implant position and of reshaping bone. As a result, accurate placement of implants may be more difficult. Conventional techniques for counteracting these problems include, for example, surgical navigation, positioning the leg for optimal joint exposure, and employing specially designed, downsized instrumentation and complex surgical techniques. Such techniques, however, typically require a large amount of specialized instrumentation, a lengthy training process, and a high degree of skill. Moreover, operative results for a single surgeon and among various surgeons are not sufficiently predictable, repeatable, and/or accurate. As a result, implant performance and longevity varies among patients.

[0007] In orthopedic applications, one drawback of both MIS and traditional surgical approaches is that healthy as well as diseased bone is removed when the bone is prepared to receive the implant. For example, a total knee replacement can require removal of up to ½ inch of bone on each of three compartments of the knee. One conventional solution for preserving healthy bone is to perform a partial (or unicompartmental) knee replacement where only one compartment of the knee is damaged. A unicompartmental approach involves removal of damaged or arthritic portions on only one compartment of the knee. For example, the REPICCI® unicondylar knee system typically requires removal of only about ¼ inch of bone on one compartment of the knee. The REPICCI® system employs freehand sculpting of bone with a spherical burr through a minimally invasive incision typically about 3 inches in length. The spherical burr enables cuts having rounded shapes that cannot be reproduced with a surgical saw. The freehand burring technique, however, is difficult to master and requires more artistic sculpting capability from the surgeon than techniques utilizing traditional cutting jigs or saw guides. As a result, freehand cutting requires a high degree of skill to achieve operable results that are sufficiently predictable, repeatable, and/or accurate. Moreover, the REPICCI® technique and traditional surgical approaches can not produce cuts having complex or highly curved geometries. Thus, such approaches typically require the removal of at least some healthy bone along with the diseased/damaged bone.

[0008] Another drawback of both MIS and traditional orthopedic surgical approaches is that such approaches do not enhance the surgeon's inherent surgical skill in a cooperative manner. For example, some conventional techniques for joint replacement include autonomous robotic systems to aid the surgeon. Such systems, however, typically serve primarily to enhance bone machining by performing autonomous cutting with a high speed burr or by moving a drill guide into place and holding the position of the drill guide while the surgeon inserts cutting tools through the guide. Although such systems enable precise bone resections for improved implant fit and placement, they act autonomously (rather than cooperatively with the surgeon) and thus require the surgeon to cede a degree of control to the robot. Additional drawbacks of autonomous systems include the large size of the robot, poor ergonomics, the need to rigidly clamp the bone during registration and cutting, increased incision length for adequate robot access, and limited acceptance by surgeons and regulatory agencies due to the autonomous nature of the system.

[0009] Other conventional robotic systems include robots that cooperatively interact with the surgeon. One drawback of conventional interactive robotic systems is that such systems lack the ability to adapt surgical planning and navigation in real-time to a dynamic intraoperative environment. For example, U.S. patent application Ser. No. 10/470,314 (Pub. No. US 2004/0128026), which is hereby incorporated by reference herein in its entirety, discloses an interactive robotic system programmed with a three-dimensional virtual region of constraint that is registered to a patient. The robotic system includes a three degree of freedom (3-DOF) arm having a handle that incorporates force sensors. The surgeon utilizes the handle to manipulate the arm to move the cutting tool. Moving the arm via the handle is required so that the force sensors can measure the force being applied to the handle by the surgeon. The measured force is then used in controlling motors to assist or resist movement of the cutting tool. For example, during a

knee replacement operation, the femur and tibia of the patient are fixed in position relative to the robotic system. As the surgeon applies force to the handle to move the cutting tool, the interactive robotic system may apply an increasing degree of resistance to resist movement of the cutting tool as the cutting tool approaches a boundary of the virtual region of constraint. In this manner, the robotic system guides the surgeon in preparing the bone by maintaining the cutting tool within the virtual region of constraint. As with the above-described autonomous systems, however, the interactive robotic system functions primarily to enhance bone machining. The interactive robotic system also requires the relevant anatomy to be rigidly restrained and the robotic system to be fixed in a gross position and thus lacks real-time adaptability to the intraoperative scene. Moreover, the 3-DOF configuration of the arm and the requirement that the surgeon manipulate the arm using the force handle results in limited flexibility and dexterity, making the robotic system unsuitable for certain MIS applications.

[0010] In view of the foregoing, a need exists for a surgical system that can replace direct visualization in minimally invasive surgery, spare healthy bone in orthopedic joint replacement applications, enable intraoperative adaptability and surgical planning, and produce operative results that are sufficiently predictable, repeatable, and/or accurate regardless of surgical skill level. A surgical system need not necessarily meet all or any of these needs to be an advance, though a system meeting these needs would me more desirable.

SUMMARY OF THE INVENTION

[0011] An aspect of the present invention relates to a surgical apparatus. The surgical apparatus includes a computer system and a surgical device configured to be manipulated by a user to perform a procedure on a patient. The computer system is programmed to implement control parameters for controlling the surgical device to provide at least one of haptic guidance to the user and a limit on user manipulation of the surgical device, based on a relationship between an anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the surgical device, and to adjust the control parameters in response to movement of the anatomy during the procedure.

[0012] Another aspect of the present invention relates to a surgical apparatus. The surgical apparatus includes a haptic device configured to be manipulated by a user to perform a procedure on a patient. The haptic device includes at least one feedback mechanism configured to supply feedback to the user manipulating the haptic device. The surgical apparatus also includes a computer system programmed to implement control parameters for controlling the at least one feedback mechanism to provide haptic guidance to the user, while the user manipulates the haptic device, based on a relationship between an anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the haptic device.

[0013] Yet another aspect of the present invention relates to a surgical method. The surgical method includes creating a representation of an anatomy of a patient; associating the anatomy and a surgical device with the representation of the anatomy; manipulating the surgical device to perform a procedure on a patient by moving a portion of the surgical device in a region of the anatomy; controlling the surgical device to provide at least one of haptic guidance and a limit on manipulation of the surgical device, based on a relationship between the representation of the anatomy and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the surgical device; and adjusting the representation of the anatomy in response to movement of the anatomy during the procedure.

[0014] Yet another aspect of the present invention relates to a surgical method. The surgical method includes creating a representation of an anatomy of a patient; associating the anatomy and a haptic device with the representation of the anatomy; and manipulating the haptic device to perform a procedure on a patient by moving a portion of the haptic device in a region of the anatomy, where the haptic device includes at least one feedback mechanism configured to supply feedback during manipulation. The surgical method further includes controlling the at least one feedback mechanism to provide haptic guidance, during manipulation of the haptic device, based on a relationship between the representation of the anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the haptic device.

[0015] Yet another aspect of the present invention relates to a method for joint replacement. The method includes creating a representation of a first bone; creating a representation of a second bone; planning bone preparation for implanting a first implant on the first bone; preparing the first bone to receive the first implant by manipulating a surgical tool to sculpt the first bone; planning bone preparation for implanting a second implant on the second bone after preparing the first bone; and preparing the second bone to receive the second implant by manipulating the surgical tool to sculpt the second bone.

[0016] Yet another aspect of the present invention relates to a surgical planning method. The surgical planning method includes detecting a height of a cartilage surface above a bone; creating a representation of the bone and a representation of the height of the cartilage surface; and planning bone preparation for implanting an implant on the bone based at least in part on the detected height of the cartilage surface.

[0017] Yet another aspect of the present invention relates to a surgical planning method. The surgical planning method includes creating a representation of a bone of a joint; moving the joint to a first position; identifying a first point corresponding to a first location in the joint, when the joint is in the first position; moving the joint to a second position; identifying a second point corresponding to a second location in the joint, when the joint is in the second position; and planning bone preparation for implanting an implant on the bone based at least in part on the first and second points.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and together with the description serve to explain principles of the invention.

[0019] **FIG. 1** is a perspective view of an embodiment of a surgical system according to the present invention.

[0020] **FIG. 2A** is a perspective view of an embodiment of a haptic device according to the present invention.

[0021] **FIG. 2B** is a perspective view of an embodiment of a haptic device according to the present invention.

[0022] **FIG. 2C** is a perspective view of the haptic device of **FIG. 2A** showing an embodiment of a manner of operating the haptic device according to the present invention.

[0023] **FIG. 3** is a perspective view of an embodiment of an end effector of the haptic device of **FIG. 2A**.

[0024] **FIG. 4** is a perspective view of an embodiment of an anatomy tracker according to the present invention.

[0025] **FIG. 5** is a perspective view of an embodiment of a haptic device tracker according to the present invention.

[0026] **FIG. 6A** is a perspective view of an embodiment of an end effector tracker according to the present invention.

[0027] **FIG. 6B** is a perspective view of the end effector of **FIG. 5A** attached to a haptic device.

[0028] **FIG. 7** is a perspective view of an embodiment of an instrument tracker according to the present invention.

[0029] **FIG. 8** is a view of an embodiment of a mechanical tracking system according to the present invention.

[0030] **FIG. 9** is a perspective view of a femur and a tibia showing an embodiment of a graphical representation of a haptic object according to the present invention.

[0031] **FIG. 10A** is a perspective view of an embodiment of a femoral component according to the present invention.

[0032] **FIG. 10B** is a perspective view of an embodiment of a tibial component according to the present invention.

[0033] **FIG. 11A** is a graph of a force feedback curve according to an embodiment of the present invention.

[0034] **FIG. 11B** is a graph of the force feedback curve of **FIG. 11A** shifted to the left.

[0035] **FIG. 11C** is a graphical representation of an embodiment of a repulsive haptic object according to the present invention.

[0036] **FIG. 11D** is a graphical representation of an embodiment of a repulsive haptic object according to the present invention.

[0037] **FIG. 11E** is a graphical representation of an embodiment of virtual tool according to the present invention.

[0038] **FIG. 11F** is a graphical representation of an embodiment of virtual tool according to the present invention.

[0039] **FIG. 11G** shows an embodiment of a graphical selection interface according to the present invention.

[0040] **FIG. 11H** shows an embodiment of a graphical selection interface according to the present invention.

[0041] **FIG. 12** shows an embodiment of a display of a CAS system according to the present invention.

[0042] **FIG. 13** is a block diagram of an embodiment of a process for a unicondylar knee replacement according to the present invention.

[0043] **FIG. 14A** shows an embodiment of a leg holder according to the present invention.

[0044] **FIG. 14B** shows an embodiment of a leg holder according to the present invention.

[0045] **FIG. 15** is a view of an embodiment of a surgical navigation screen showing a segmentation step according to the present invention.

[0046] **FIG. 16** is a view of an embodiment of a surgical navigation screen showing a segmentation step according to the present invention.

[0047] **FIG. 17** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0048] **FIG. 18** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0049] **FIG. 19** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0050] **FIG. 20** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0051] **FIG. 21** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0052] **FIG. 22** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0053] **FIG. 23** is a view of an embodiment of a surgical navigation screen showing a landmark selection step according to the present invention.

[0054] **FIG. 24** is a view of an embodiment of a surgical navigation screen showing a probe calibration verification step according to the present invention.

[0055] **FIG. 25** is a view of an embodiment of a surgical navigation screen showing an anatomy tracker installation step according to the present invention.

[0056] **FIG. 26** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0057] **FIG. 27** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0058] **FIG. 28** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0059] **FIG. 29** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0060] **FIG. 30** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0061] **FIG. 31** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0062] **FIG. 32** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0063] **FIG. 33** is a view of an embodiment of a surgical navigation screen showing a registration step according to the present invention.

[0064] **FIG. 34** is a view of an embodiment of a surgical navigation screen showing a haptic device calibration step according to the present invention.

[0065] **FIG. 35** is a view of an embodiment of a surgical navigation screen showing an implant placement planning step according to the present invention.

[0066] **FIG. 36** is a view of an embodiment of a surgical navigation screen showing a bone preparation step according to the present invention.

[0067] **FIG. 37** is a view of an embodiment of a surgical navigation screen showing a bone preparation step according to the present invention.

[0068] **FIG. 38** is a view of an embodiment of a surgical navigation screen showing an implant placement planning step according to the present invention.

[0069] **FIG. 39** is a view of an embodiment of a surgical navigation screen showing a bone preparation step according to the present invention.

[0070] **FIG. 40** is a block diagram of an embodiment of a haptic rendering process according to the present invention.

[0071] **FIG. 41** is a representation of multiple haptic objects that are superimposed.

[0072] **FIG. 42** is a representation of an embodiment of a 3D geometric haptic object according to the present invention.

[0073] **FIG. 43** is a block diagram of an embodiment of a polygon based haptic rendering process according to the present invention.

[0074] **FIG. 44** is a representation of an embodiment of a polygon surface object according to the present invention.

[0075] **FIG. 45** is a representation of an embodiment of a voxel map according to the present invention.

[0076] **FIG. 46A** is a representation of an embodiment of a voxel lookup table according to the present invention.

[0077] **FIG. 46B** is a representation of an embodiment of a polygon lookup table according to the present invention.

[0078] **FIG. 47** illustrates an implementation of an embodiment of a virtual guide line according to the present invention.

[0079] **FIG. 48** is a graphical illustration of a coordinate transformation.

[0080] **FIG. 49A** is an illustration of a virtual proxy point location.

[0081] **FIG. 49B** is an illustration of a virtual proxy point location.

[0082] **FIG. 50** is a flowchart of an embodiment of a haptic rendering algorithm according to the present invention.

[0083] **FIG. 51A** is an pictorial representation of an active polygon priority behavior.

[0084] **FIG. 51B** is a pictorial representation of an On-Polygon priority behavior.

[0085] **FIG. 51C** is a pictorial representation of a continuous surface priority behavior.

[0086] **FIG. 51D** is a pictorial representation of a minimum force priority behavior.

[0087] **FIG. 52A** is a pictorial representation of an x-y view of an augmenting concave corner behavior.

[0088] **FIG. 52B** is a pictorial representation of a y-z view of an augmenting concave corner behavior.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0089] Presently preferred embodiments of the invention are illustrated in the drawings. Although this specification refers primarily to orthopedic procedures involving the knee joint, it should be understood that the subject matter described herein is applicable to other joints in the body, such as, for example, a shoulder, elbow, wrist, spine, hip, or ankle and to any other orthopedic and/or musculoskeletal implant, including implants of conventional materials and more exotic implants, such as orthobiologics, drug delivery implants, and cell delivery implants.

[0090] **FIG. 1** shows an embodiment of a surgical system **10** according to the present invention. The surgical system **10** includes a computing system **20**, a haptic device **30**, and a tracking (or localizing) system **40**. In operation, the surgical system **10** enables comprehensive, intraoperative surgical planning. The surgical system **10** also provides haptic guidance to a user (e.g., a surgeon) and/or limits the user's manipulation of the haptic device **30** as the user performs a surgical procedure.

[0091] The computing system **20** includes hardware and software for operation and control of the surgical system **10**. As shown in **FIG. 1**, the computing system **20** includes a computer **21**, a display device **23**, and an input device **25**. The computing system **20** may also include a cart **29**.

[0092] The computer **21** may be any known computing system but is preferably a programmable, processor-based system. For example, the computer **21** may include a microprocessor, a hard drive, random access memory (RAM), read only memory (ROM), input/output (I/O) circuitry, and any other well-known computer component. The computer **21** is preferably adapted for use with various types of storage devices (persistent and removable), such as, for example, a portable drive, magnetic storage (e.g., a floppy disk), solid state storage (e.g., a flash memory card), optical storage (e.g., a compact disc or CD), and/or network/Internet storage. The computer **21** may comprise one or more computers, including, for example, a personal computer (e.g., an IBM-PC compatible computer) or a workstation (e.g., a SUN or Silicon Graphics workstation) operating under a Windows, MS-DOS, UNIX, or other suitable operating system and preferably includes a graphical user interface (GUI). In one embodiment, the computer **21** includes a Navigation Module available from MAKO SURGICAL CORP.™ and identified by product number 0040TAS00001.

[0093] The display device **23** is a visual interface between the computing system **20** and the user. The display device **23** is connected to the computer **21** and may be any device suitable for displaying text, images, graphics, and/or other visual output. For example, the display device **23** may include a standard display screen (e.g., LCD, CRT, plasma, etc.), a touch screen, a wearable display (e.g., eyewear such as glasses or goggles), a projection display, a head-mounted display, a holographic display, and/or any other visual output device. The display device **23** may be disposed on or near the computer **21** (e.g., on the cart **29** as shown in **FIG. 1**) or may be remote from the computer **21** (e.g., mounted on a wall of an operating room or other location suitable for viewing by the user). The display device **23** is preferably adjustable so that the user can position/reposition the display device **23** as needed during a surgical procedure. For example, the display device **23** may be disposed on an adjustable arm (not shown) that is connected to the cart **29** or to any other location well-suited for ease of viewing by the user. The display device **23** may be used to display any information useful for a medical procedure, such as, for example, images of anatomy generated from an image data set obtained using conventional imaging techniques, graphical models (e.g., CAD models of implants, instruments, anatomy, etc.), graphical representations of a tracked object (e.g., anatomy, tools, implants, etc.), digital or video images, registration information, calibration information, patient data, user data, measurement data, software menus, selection buttons, status information, and the like.

[0094] In addition to the display device **23**, the computing system **20** may include an acoustic device (not shown) for providing audible feedback to the user. The acoustic device is connected to the computer **21** and may be any known device for producing sound. For example, the acoustic device may comprise speakers and a sound card, a motherboard with integrated audio support, and/or an external sound controller. In operation, the acoustic device may be adapted to convey information to the user. For example, the computer **21** may be programmed to signal the acoustic device to produce a sound, such as a voice synthesized verbal indication "DONE," to indicate that a step of a surgical procedure is complete. Similarly, the acoustic device may be used to alert the user to a sensitive condition, such as producing a beep to indicate that a surgical cutting tool is nearing a critical portion of soft tissue.

[0095] The input device **25** of the computing system **20** enables the user to communicate with the surgical system **10**. The input device **25** is connected to the computer **21** and may include any device enabling a user to provide input to a computer. For example, the input device **25** can be a known input device, such as a keyboard, a mouse, a trackball, a touch screen, a touch pad, voice recognition hardware, dials, switches, buttons, a trackable probe, a foot pedal, a remote control device, a scanner, a camera, a microphone, and/or a joystick.

[0096] The computing system **20** (in whole or in part) may be disposed on the cart **29** to economize space, minimize a physical footprint of the computing system **20**, and/or permit portability. The cart **29** may be, for example, a known cart, platform, or equipment stand and is preferably configured for ease of mobility of the computing system **20**. For example, as shown in **FIG. 1**, the cart **29** may include rolling members **28** (e.g., wheels or casters) to enable the cart **29** to be moved. The cart **29** may also include a mechanism for securing the cart **29** in position. For example, the cart **29** may be equipped with wheel locks or brakes for the rolling members **28**, a foot pedal locking device, jack stands, and/or any other known mechanism for securing a cart in position. In this manner, the cart **29** enables the computing system **20** to be moved from one location to another, positioned as necessary for each surgical case, and secured in a desired position during storage and surgery. Alternatively, the computing system **20** (in whole or in part) may be installed in a room where a surgical procedure will be performed (e.g., mounted on a wall or workstation), installed in a remote location, integrated with the haptic device **30**, integrated with an imaging device (e.g., a computed tomography (CT) device, a magnetic resonance imaging (MRI) device, a fluoroscopic device, an ultrasound device, etc.), and/or integrated with an medical system (e.g., a medical equipment cart in a room where a surgical procedure will be performed).

[0097] The computing system **20** is adapted to enable the surgical system **10** to perform various functions related to surgical planning, navigation, image guidance, and/or haptic guidance. For example, the computer **21** may include algorithms, programming, and software utilities related to general operation, data storage and retrieval, computer aided surgery (CAS), applications, haptic control, and/or any other suitable functionality. In one embodiment, the computing system **20** includes software used in a Navigation Module currently available from MAKO SURGICAL CORP.™ and identified by product number 0040TAS00001.

[0098] Utilities related to general operation are configured to provide basic computing functions that enable and support overall operation of the surgical system **10**. General operation utilities may include, for example, well known features such as functions for fast graphics processing, functions for supporting input/output (I/O) devices, functions for connecting to a hospital network, functions for managing database libraries (e.g., implant and instrument databases), functions for system security (e.g., login features, access restrictions, etc.), and/or any other functionality useful for supporting overall operation of the surgical system **10**.

[0099] Utilities related to data storage and retrieval are configured to enable storage of and access to various forms of data, such as image data (e.g., two- or three-dimensional image data sets obtained using any suitable imaging modality, such as, for example, x-ray, computed tomography (CT), magnetic resonance (MR), positron emission tomography (PET), single photon emission computed tomography (SPECT), ultrasound, etc.), application data, implant data, instrument data, anatomical model data, patient data, user preference data, and the like. The data storage and retrieval utilities may include any functionality appropriate for storing and handling relevant data.

[0100] Utilities related to computer aided surgery are configured to enable surgical planning, navigation, and basic image guided surgery capabilities. For example, as is well known, the CAS utilities may include functions for generating and displaying images from image data sets, functions for determining a position of a tip and an orientation of an axis of a surgical instrument, and functions for registering a patient and an image data set to a coordinate frame of the

tracking system **40**. These functions enable, for example, the computing system **20** to display on the display device **23** a virtual representation of a tracked surgical instrument overlaid on one or more images of a patient's anatomy and to update the virtual representation of the tracked instrument in real time during a surgical procedure. Images generated from the image data set may be two-dimensional or, in the case of a three-dimensional image data set, a three-dimensional reconstruction based, for example, on segmentation of the image data set. When more than one image is shown on the display device **23**, the computing system **20** preferably coordinates the representation of the tracked instrument among the different images. In addition to or in lieu of images generated from image data sets, the computing system **20** may use anatomical models (e.g., based on CAD models, line art, sketches, cartoons, artist renderings, generic or morphed data sets, etc.).

[0101] Utilities related to applications of the surgical system **10** include application specific programs configured to assist the user with surgical planning and navigation. Programs associated with the application utilities may be configured for use in various medical procedures and/or may be customized for a specific procedure. For example, the application utilities may include programs related to one or more orthopedic procedures, such as, for example, total knee replacement, partial knee replacement, hip replacement, shoulder replacement, elbow replacement, wrist replacement, ankle replacement, spinal surgery, and/or installation of orthopedic and/or musculoskeletal implants, including implants of conventional materials and more exotic implants, such as orthobiologics, drug delivery implants, and cell delivery implants. The application utilities may be directed to various aspects of surgical planning and navigation, including pre-operative, intra-operative, and post-operative activities. For example, the application utilities may include programs or processes directed to planning and set up, such as, for example, system initialization processes, planning processes, visualization processes, diagnostic imaging processes, registration processes, and calibration processes. The application utilities may also include programs or processes directed to object tracking and system control, such as, for example, coordinate transform processes, interpolation processes, tool and power control processes, anatomy positioning processes, mode control processes, safety processes, occlusion detection algorithms, and forward kinematics algorithms. The application utilities may include programs or processes related to the haptic device **30**, such as, for example, haptic force computation processes, haptic force mapping processes, processes for generating haptic objects, and haptic rendering algorithms. The application utilities may also include programs and processes for communicating with the user during a surgical procedure, such as, for example, software for displaying pages or images corresponding to specific steps of a surgical procedure, software for prompting a user to perform a certain task, and software for providing feedback (e.g., visual, audible, tactile, and/or force feedback) to the user.

[0102] Utilities related to haptic control are configured to perform various functions related to control, performance, stability, and/or safety of the haptic device **30**. For example, the haptic control utilities may include a real time operating system (RTOS), motion control software, hardware and software for generating high frequency updates for control of the haptic device **30**, software for ensuring failsafe operation of the haptic device **30** (e.g., control of brakes, monitoring of redundant sensors, etc.), and/or any other utility suitable for improving or promoting performance, stability, and/or safety of the haptic device **30**. The haptic control utilities may be executed on the computer **21** of the computing system **20** provided the computer **21** has a computing architecture sufficient to support the operating requirements of the haptic control utilities. For example, processes associated with haptic control typically have higher operational frequency requirements that other processes running on the computer **21**. In one embodiment, the haptic control processes operate at a frequency of approximately 2 kHz. In another embodiment, the haptic control processes operate at a frequency in a range of between about 0.1 kHz to about 10 kHz. In yet another embodiment, the haptic control processes operate at a frequency in a range of between about 500 Hz to about 2,400 Hz. In contrast, the computer **21** may operate at a substantially lower frequency, such as, for example, a frequency in a range of about 15 Hz to about 20 Hz. In another embodiment, the frequency of the computer **21** may be in a range of between about 2 Hz to about 60 Hz. In other embodiments, the frequency of the computer **21** may be substantially equivalent to the operating frequency required by the haptic control processes (e.g., approximately 2 kHz). If the computer **21** does not have an architecture sufficient to support operation of the haptic control processes, the computing system **20** may include a computer **31** for execution of the haptic control utilities. In a preferred embodiment, the computer **31** is integrated or embedded with the haptic device **30**.

[0103] The computer **31** (shown in **FIG. 1**) may be similar to the computer **21** but is preferably configured to satisfy specific operational requirements of the haptic device **30**, such as, for example, the need for higher operating frequencies. The computer **31** may comprise one or more computers. In one embodiment, the computer **31** is an Intel compatible x86 3U CompactPCI single-board computer with a processor clock speed of at least 1.6 GHz, at least 2 GByte of non-volatile storage (e.g., hard disk drive, Compact FLASH, etc.), at least 256 MB of RAM, 400 MHz Front Side Bus or faster, at least 1 MByte of Level 2 cache memory, and a real-time operating system. One such commercially available embodiment includes the ICP-PM-1004-DG-8A computer from Inova Computers GmbH, used with the QNX 6.1 (or later) operating system from QNX Software Systems Ltd.

[0104] In addition to the haptic control utilities, the computer **31** may include programs that enable the haptic device **30** to utilize data from the tracking system **40**. For example, the tracking system **40** may generate tracked object pose (e.g., position and orientation) data periodically. In one embodiment, the object pose data is generated approximately 30 times a second or 30 Hz. In other embodiments, object pose data is generated more frequently such as, for example, at approximately 500 Hz or greater. The object posed data is transferred from the tracking system **40** to the computer **31** (e.g., via an interface **100***b*) and may be conditioned in any conventional manner such as, for example, using a noise filter as is well known. Additionally, in embodiments where the tracking system **40** operates at a lower frequency than the haptic control processes, the object pose data may be conditioned using an interpolation filter as is well known. The interpolation filter smoothes the object pose data by populating gaps between discrete data samples

to enable the object pose data to be used in the higher frequency haptic control processes. The computer **31** may also include a coordinate transform process for mapping (or transforming) coordinates in one space to those in another to achieve spatial alignment or correspondence. For example, the surgical system **10** may use the coordinate transform process to map positions of tracked objects (e.g., surgical tools, patient anatomy, etc.) into a coordinate system used by a process running on the computer **31** and/or the computer **21**. As is well known, the coordinate transform process may include any suitable transformation technique, such as, for example, rigid-body transformation, non-rigid transformation, affine transformation, and the like.

[**0105**] One advantage of including multiple computers (e.g., the computer **21** and the computer **31**) in the computing system **20** is that each computer can be independently configured. Thus, the computer **21** can be customized for surgical planning and navigation, and the computer **31** can be customized for controlling performance, stability, and/or safety of the haptic device **30**. For example, the computer **31** may include a real time operating system (RTOS) to maintain dependable updates to the haptic control system and a stable operating platform for the haptic device **30**. In contrast, the computer **21** may include a non-RTOS because the computing system **20** may not require the same degree of stability as the haptic device **30**. Thus, the computer **21** may instead be customized to meet specific requirements of surgical navigation, such as, for example, graphics processing. Another advantage of multiple computers having separate computing architectures is that software developers with limited knowledge of haptic systems can create CAS utilities for the computer **21** that can be used in conjunction with a variety of haptic devices. Similarly, software developers with limited knowledge of CAS can create haptic utilities focused on enhancing the performance, stability, and/or safety of a particular haptic device. As an alternative to separate computers, the computing functions of the haptic device **30** and the computing system **20** may be incorporated, for example, into a single computer (e.g., the computer **21** or the computer **31**), into a computing system of an imaging device (e.g., a CT device, an MRI device, a fluoroscopic device, etc.), and/or into a hospital computing system (e.g., a network system, an equipment cart in a room where the surgical procedure will be performed, etc.).

[**0106**] As shown in **FIG. 1**, the computing system **20** is coupled to the haptic device **30** via an interface **100***a*. The interface **100***a* includes a physical interface and a software interface. The physical interface may be any known interface such as, for example, a wired interface (e.g., serial, USB, Ethernet, CAN bus, and/or other cable communication interface) and/or a wireless interface (e.g., wireless Ethernet, wireless serial, infrared, and/or other wireless communication system). The software interface may be resident on the computer **21** and/or the computer **31** and enables the computing system **20** to communicate with and control operation of the haptic device **30**. In one embodiment, the software interface includes a utility that allows the computing system **20** to issue commands to the haptic device **30**. For example, the computer **21** may send a command to the computer **31** requesting the haptic device **30** to enter a specific mode (e.g., approach mode, haptic mode, free mode, input mode, hold mode). In response, the computer **31** may be programmed to check various parameters to verify that entry into the requested mode is safe and otherwise acceptable and to either enter the haptic device **30** into the requested mode or return an appropriate error message.

[**0107**] The haptic device **30** is a surgical device configured to be manipulated by a user to move a surgical tool **50** to perform a procedure on a patient. During the procedure, the computing system **20** implements control parameters for controlling the haptic device **30** based, for example, on a relationship between an anatomy of the patient and a position, an orientation, a velocity, and/or an acceleration of a portion of the haptic device **30** (e.g., the surgical tool **50**). In one embodiment, the haptic device **30** is controlled to provide a limit on user manipulation of the device (e.g., by limiting the user's ability to physically manipulate the haptic device **30**). In another embodiment, the haptic device **30** is controlled to provide haptic guidance (i.e., tactile and/or force feedback) to the user. "Haptic" refers to a sense of touch, and the field of haptics involves research relating to human interactive devices that provide tactile and/or force feedback to an operator. Tactile feedback generally includes tactile sensations such as, for example, vibration, whereas force feedback refers to feedback in the form of force (e.g., resistance to movement) and/or torque (also known as "wrench). Wrench includes, for example, feedback in the form of force, torque, or a combination of force and torque.

[**0108**] Guidance from the haptic device **30** coupled with computer aided surgery (CAS) enables a surgeon to actively and accurately control surgical actions (e.g., bone cutting) and delivery of localized therapies (e.g., in the brain). For example, the computing system **20** may be programmed to determine the control parameters based on data representative of a patient's anatomy (e.g., preoperative CT image data, ultrasound data); a virtual (or haptic) object associated with (or registered to) the anatomy; a parameter relative to the anatomy (e.g., a depth defined with respect to a portion of the anatomy); and/or the anatomy. The computing system **20** can control the haptic device **30** to generate a force, a torque, and/or vibration based on the position of the tool **50** relative to the virtual object, the parameter, and/or the anatomy. For example, the tool **50** may be constrained against penetrating a virtual boundary associated with a representation of the anatomy and/or constrained against exceeding a parameter defined with respect to the representation of the anatomy. Thus, in operation, as a surgeon manipulates the haptic device **30** to move the tool **50**, virtual pathways may be used to guide the tool **50** to specific targets, virtual boundaries may be used to define cutting shapes or to prevent the tool **50** from contacting critical tissue, and predefined parameters may be used to limit travel of the tool **50** (e.g., to a predefined depth). The computing system **20** may also be programmed to adjust the control parameters in response to movement of the physical anatomy during the procedure (e.g., by monitoring detected movement of the physical anatomy and then adjusting the virtual object in response to the detected movement). In this manner, the surgical system **10** can supplement or replace direct visualization of the surgical site, enhance the surgeon's natural tactile sense and physical dexterity, and facilitate the targeting, repairing, and replacing of various structures in the body through conventionally sized portals (e.g., 12 inches or greater in length) to portals having a diameter as small as approximately 1 mm.

[**0109**] In orthopedic applications, for example, the haptic device **30** can be applied to the problems of inaccuracy, unpredictability, and non-repeatability in bone preparation by assisting the surgeon with proper sculpting of bone to thereby enable precise, repeatable bone resections while

maintaining intimate involvement of the surgeon in the bone preparation process. Moreover, because the haptic device **30** haptically guides the surgeon in the bone cutting operation, the skill level of the surgeon is less critical. As a result, surgeons with varying degrees of skill and experience are able perform accurate, repeatable bone resections. In one embodiment, for example, a surgical tool is coupled to the haptic device **30**. The surgeon can operate the tool to sculpt bone by grasping and moving the tool and/or by grasping and manipulating the haptic device **30** to move the tool. As the surgeon performs the cutting operation, the surgical system **10** tracks the location of the tool (with the tracking system **40**) and, in most cases, allows the surgeon to freely move the tool in the workspace. When the tool is in proximity to a virtual boundary in registration with the patient, however, the surgical system **10** controls the haptic device **30** to provide haptic guidance that tends to constrain the surgeon from penetrating the virtual boundary with the tool. For example, the virtual boundary may be defined by a haptic object, and the haptic guidance may comprise an output wrench (i.e., force and/or torque) that is mapped to the haptic object and experienced by the surgeon as resistance to further tool movement in the direction of the virtual boundary. Thus, the surgeon may feel as if the tool has encountered a physical object, such as a wall. In this manner, the virtual boundary functions as a virtual cutting guide. Thus, the haptic device **30** communicates information to the surgeon regarding the location of the tool relative to the virtual boundary and provides physical guidance in the actual cutting process. The haptic device **30** may also be configured to limit the user's ability to manipulate the surgical tool as described, for example, in U.S. patent application Ser. No. 10/470,314 (Pub. No. US 2004/0128026), which is hereby incorporated by reference herein in its entirety.

[**0110**] The haptic device **30** may include a mechanical or electromechanical device adapted to transmit tactile feedback (e.g., vibration) and/or force feedback (e.g., wrench) to the user. The haptic device **30** may be robotic, non-robotic, or a combination of robotic and non-robotic systems. For example, the haptic device **30** may include a haptic device as described in U.S. patent application Ser. No. 10/384,072, filed Mar. 6, 2003, published Feb. 5, 2004; U.S. patent application Ser. No. 10/384,077, filed Mar. 6, 2003, published Feb. 19, 2004; U.S. patent application Ser. No. 10/384,078, filed Mar. 6, 2003, published Feb. 19, 2004; U.S. patent application Ser. No. 10/384,194, filed Mar. 6, 2003, published Feb. 19, 2004; U.S. patent application Ser. No. 10/621,119, filed Jul. 16, 2003, published Jun. 3, 2004; and/or U.S. Provisional Patent Application Ser. No. 60/655,642, filed Feb. 22, 2005. Each of the above-referenced published applications is hereby incorporated by reference herein in its entirety.

[**0111**] In one embodiment, the haptic device **30** comprises a robot. In this embodiment, as shown in **FIG. 2A**, the haptic device **30** includes a base **32**, an arm **33**, an end effector **35**, and a user interface **37**. The haptic device **30** may also include a platform **39**.

[**0112**] The base **32** provides a foundation for the haptic device **30**. As shown in **FIG. 2**, the base **32** supports the arm **33** and may also house and/or support other components of the haptic device **30**, such as, for example, controllers, amplifiers, actuators, motors, transmission components, clutches, brakes, power supplies, sensors, computer hardware, and/or any other well-known robotic component. The base **32** may be made of any suitable metallic and/or synthetic material, such as, for example, aluminum or plastic, and preferably includes removable panels to provide access to components housed within the base **32**.

[**0113**] The arm **33** is disposed on the base **32** and is adapted to enable the haptic device **30** to be manipulated by the user. The arm **33** may be any suitable mechanical or electromechanical structure but is preferably an articulated arm having four or more degrees of freedom (or axes of movement), such as, for example, a robotic arm known as the "Whole-Arm Manipulator" or WAM™ currently manufactured by Barrett Technology, Inc. In one embodiment, the arm **33** includes a first segment **33***a*, a second segment **33***b*, and a third segment **33***c* as shown in **FIG. 2A**. The first segment **33***a* and the second segment **33***b* are connected at a first joint **33***d* (e.g., a shoulder joint), and the second segment **33***b* and the third segment **33***c* are connected at a second joint **33***e* (e.g., an elbow joint). As shown in **FIG. 2B**, the arm **33** may have, for example, a first degree of freedom DOF_1, a second degree of freedom DOF_2, a third degree of freedom DOF_3, and a fourth degree of freedom DOF_4. Thus, the segments **33***a*, **33***b*, and **33***c* and the joints **33***e* and **33***d* form an articulating mechanical linkage that can be manipulated into various positions or poses. The arm **33** is sized to be appropriate for use in a variety of procedures, such as orthopedic, neurological, and/or trauma procedures, and to be sufficiently compact to enable mobility of the haptic device **30** and efficient positioning of the haptic device **30** in an operating room. For example, the arm **33** may be sized slightly larger than a human arm. In one embodiment, the arm **33** has a reach of approximately 1 m, and a diameter of the segments **33***b* and **33***c* is approximately 89 mm. The arm **33** may also be adapted to house and/or route components of the haptic device **30**, such as, for example, instrumentation, power lines, motors, transmission components, controllers, actuators, amplifiers, brakes, clutches, power supplies, sensors, and/or computer hardware. For example, the segments **33***a*, **33***b*, and **33***c* may include internal channels and/or hollow portions within which components of the haptic device **30** may be disposed. The segments **33***a*, **33***b*, and **33***c* may be made of any suitable metallic and/or synthetic material, such as, for example, aluminum or plastic, and preferably include removable panels and/or access ports to enable access to components housed within the arm **33**.

[**0114**] Dexterity of the arm **33** may be enhanced, for example, by adding additional degrees of freedom. For example, the arm **33** may include a wrist **36**. As shown in **FIG. 2A**, the wrist **36** may be disposed on the arm **33** (e.g., at a distal end of the third segment **33***c*) and includes one or more degrees of freedom to augment the degrees of freedom DOF_1, DOF_2, DOF_3, and DOF_4 of the arm **33**. For example, as shown in **FIG. 2B**, the wrist **36** may include a degree of freedom DOF_5. In one embodiment, the wrist **36** includes two degrees of freedom, and the degree of freedom DOF_3 of the arm **33** is eliminated. The wrist **36** may also be a one degree of freedom or a three degree of freedom WAM™ wrist manufactured by Barrett Technology, Inc.

[**0115**] The arm **33** incorporates a feedback mechanism to enable the haptic device **30** to communicate information to the user while the user manipulates the haptic device **30**. In operation, the computing system **20** controls the feedback

mechanism to generate and convey tactile and/or force feedback to the user to communicate, for example, information about a location of a portion of the haptic device (e.g., the tool **50**) relative to a virtual object, a parameter relative to the anatomy, and/or the anatomy. The feedback mechanism is preferably configured to produce force, torque, and/or vibration. The feedback mechanism may incorporate a drive system (not shown) comprising one or more actuators (e.g., motors) and a mechanical transmission. The actuators are preferably adapted to supply force feedback opposing the user's manipulation of the haptic device **30**. The actuators may include, for example, a samarium-cobalt brushless motor driven by sinusoidally-commutated current amplifier/controllers, a neodymium-iron brushless motor driven by space-vector-commutated current amplifier/controllers, and/or any other suitable motor and commutation scheme suitable for use in a robotic system. The transmission may be, for example, a tension-element drive system (e.g., a cable, steel tape, or polymeric tendon transmission), a direct drive system, and/or any other low static friction and low backlash transmission system suitable for use in a robotic system. In an exemplary embodiment, the drive system includes a high-speed cable transmission and zero backlash, low friction, cabled differentials. In one embodiment, the cable transmission may be a cable transmission used in the WAM™ robotic arm manufactured by Barrett Technology, Inc. and/or a cable transmission as described in U.S. Pat. No. 4,903,536, which is hereby incorporated by reference herein in its entirety. One advantage of a cable transmission is that the cable transmission permits most of the bulk of the arm **33** to be disposed a sufficient distance from the surgical site so that the user is not hindered or impeded by the structure or components of the arm **33** during a surgical procedure. The drive system is preferably configured for low friction, low inertia, high stiffness, large bandwidth, near-zero backlash, force fidelity, and/or backdrivability and may also be also be adapted to help maintain the arm **33** in a state where the user perceives the arm **33** as weightless. For example, in one embodiment, the arm **33** may have a configuration that is substantially balanced. Any imbalance in the arm (e.g., due gravitational effects) can be counteracted, for example, by controlling the drive system to generate forces and/or torques to correct the imbalanced condition. The motors of the drive system may also be configured to produce oscillations or vibrations so that the haptic device **30** can provide tactile feedback to the user. In addition to the drive system, the feedback mechanism may also include a vibratory device, such as an oscillator, separate from the motors for producing vibration.

[**0116**] The arm **33** may include position sensors (not shown) for determining a position and orientation (i.e., pose) of the arm **33**. The position sensors may include any known sensor for determining or tracking a position of an object, such as, for example, encoders, resolvers, potentiometers, linear variable differential transformers (LVDTs), tilt sensors, heading (compass) sensors, gravity direction sensors (e.g., accelerometers), optical sensors (e.g., infrared, fiber optic, or laser sensors), magnetic sensors (e.g., magnetoresistive or magnetorestrictive sensors), and/or acoustic sensors (e.g., ultrasound sensors). The position sensors may be disposed at any suitable location on or within the haptic device **30**. For example, the position sensors may include encoders mounted on the joints **33***d* and **33***e* and/or resolvers mounted on a shaft of each motor. The pose of the arm **33** may also be tracked using any tracking system suitable for use in a surgical environment, such as, for example, an optical, magnetic, radio, or acoustic tracking system, including the tracking system **40** described below.

[**0117**] In addition to the position sensors, the arm **33** may include redundant sensors (not shown). The redundant sensors are similar to the position sensors and may be used to detect discrepancies and/or instability during operation of the haptic device **30**. For example, differences in output of the redundant sensors and output of the position sensors may indicate a problem with the drive system and/or the position sensors. Redundant sensors can also improve accuracy in determining the pose of the arm **33** by providing data that enables a control system of the haptic device **30** to reduce or eliminate the effect of deflection in components of the drive system and/or the arm **33**. The redundant sensors are particularly advantageous when the arm **33** includes a cable transmission.

[**0118**] The end effector **35** comprises a working end of the haptic device **30** and is configured to enable the user to perform various activities related to a surgical procedure. For example, in one embodiment, the end effector **35** functions as an adapter or coupling between the arm **33** and the tool **50**. By interchanging one tool **50** for another, the user can utilize the haptic device **30** for different activities, such as registration, bone preparation, measurement/verification, and/or implant installation. In one embodiment, as shown in **FIG. 2A**, the end effector **35** includes a proximal portion adapted to be connected to the arm **33** and a distal portion that includes a device or tool **50**. The tool **50** may be, for example, a surgical tool (such as a burr, drill, probe, saw, etc.), medical device, microscope, laser range finder, camera, light, endoscope, ultrasound probe, irrigation device, suction device, radiotherapy device, and/or any other component useful for surgery, surgical planning, and/or surgical navigation. The end effector **35** is preferably configured to removably engage the tool **50** so that the user can install the appropriate tool **50** for a particular procedure and interchange tools as necessary. For example, the tool **50** may be secured to the end effector **35** with conventional hardware (e.g., screws, pins, clamps, etc.), a keyed connection, detents, threaded connectors, an interference fit, and the like. Alternatively, the tool **50** may be an integral part of the end effector **35** so that the entire end effector **35** is replaced when the user desires to interchange tools. The tool **50** is preferably moveable with respect to the arm **33** to enable the user to control a precise position of the tool **50**. For example, the tool **50** may be rotatable about an axis C-C (shown in **FIG. 2C**). In one embodiment, as shown in **FIG. 3**, the tool **50** includes a tool holder **51** received in an aperture **52** in the distal portion of the end effector **35**. The tool holder **51** may be secured in the aperture in any known manner, such as, for example, with keyed or threaded connection. The tool holder **51** is configured to releasably engage the tool **50** (e.g., a tip of a spherical burr) and may include a power line (not shown) for supplying electrical (or pneumatic) power to the tool **50**. In one embodiment, the tool holder **51** includes a motor for driving the tool **50** (e.g., a burr, saw, or other power tool). The tool **50** may be a single tool or may include multiple tools. For example, the tool **50** may comprise a spherical burr for bone cutting as well as suction and irrigation lines for cleaning the surgical site during a cutting operation. In one embodiment, the tool **50** and the tool holder **51** comprise an electric, air cooled surgical tool

currently manufactured by ANSPACH® and having product numbers EMAX2 (motor), EMAX2-FP (foot pedal), SC2000 (console), L-2SB (2 mm fluted ball), L-4B (4 mm fluted ball), L-6B (6 mm fluted ball), and L-1R (12) (1.2 mm×12.8 mm fluted router). The end effector **35** is mechanically and electrically connected to the distal end of the arm **33** in any conventional manner and may include one or more lines for supplying power, compressed air, suction, irrigation, and the like to the tool **50**.

[**0119**] The end effector **35** may also be configured to enable the user to input information into the surgical system **10**. For example, in one embodiment, the end effector **35** is adapted to function as an input device, such as a joystick. In this embodiment, the end effector **35** includes one or more degrees of freedom to enable joystick functionality. As shown in **FIG. 3**, the end effector **35** may have a single degree of freedom that permits the end effector **35** to rotate about an axis A-A. Thus, the user can rotate (or twist) the end effector **35** about the axis A-A to provide input to the surgical system **10**. When the user rotates the end effector **35**, a corresponding encoder signal indicating an amount and direction of rotation may be relayed to the computer **21** and/or the computer **31**. For example, rotation in a first direction about the axis A-A by a specified number of degrees could indicate "forward" (e.g., proceed to another step in the procedure or to another application, advance a screen on the display device **23** to a subsequent screen, etc.), and rotation in a second direction about the axis A-A by a specified number of degrees could indicate "back" (e.g., return to a previous step in the procedure or to another application, go back to a previous screen on the display device **23**, etc.). The end effector **35** (and/or other part of the arm **33**) may also include additional degrees of freedom enabling additional input. In addition to joystick functionality, the end effector **35** (and/or any other portion of the haptic device **30**) may include one or more buttons, dials, and/or switches to enable input. In this manner, efficiency and ease of use of the surgical system **10** is improved by providing a convenient input mechanism for the user.

[**0120**] The user interface **37** of the haptic device **30** enables physical interaction between the user and the haptic device **30**. For example, the interface **37** may be configured so that the user can physically contact the interface **37** and manipulate the tool **50** while simultaneously receiving haptic guidance from the haptic device **30**. The interface **37** may be a separate component affixed to the haptic device **30** (such as a handle or hand grip) or may simply be part of the existing structure of the haptic device **30**. For example, the interface **37** may be associated with the arm **33**, the end effector **35**, and/or the tool **50**. Because the interface **37** is affixed to or is an integral part of the haptic device **30**, any tactile or force feedback output by the haptic device **30** is transmitted directly to the user when the user is in contact with the interface **37**. In one embodiment, as shown in **FIG. 2A**, the user interface **37** comprises a first part (e.g., the elbow joint **33***e* of the arm **33**) configured to enable the user to change a configuration of the arm **33** and a second part (e.g., the tool **50** and/or a distal end of the arm **33** such as the end effector **35**) configured to enable the user to move the tool **50** relative to the arm **33**. In operation, as shown in **FIG. 2C**, a user **160** places one hand on the first part (e.g., the elbow joint **33***e*) and grasps the second part (e.g., the tool **50**) with the other hand. The user **160** then exerts force as needed to manipulate the arm **33** and move the tool **50**. In this manner, the user manipulates the interface **37** to simultaneously change a configuration of the arm **33** and move the tool **50** relative to the arm **33**. Contacting the haptic device **30** in dual locations (e.g., the tool **50** and the elbow joint **33***e*) advantageously allows both gross and fine control of the haptic device **30**. For example, the user **160** is able to simultaneously control both a gross configuration of the arm **33** (e.g., via the elbow joint **33***e*) and a fine (or precise) location of a tip of the tool **50** (e.g., by moving the tool **50** relative to the arm **33**), which is important in performing activities requiring a high degree of accuracy and dexterity, such as, for example, maneuvering the tool **50** to the surgical site and sculpting bone.

[**0121**] The user interface **37** is preferably sized so that the user can easily grip the interface **37**. For example, a diameter of the interface **37** may correspond to a diameter that is easily grasped by a hand and/or finger(s) of a user. The diameter of the interface **37** may be, for example, in a range of approximately 5 mm to approximately 75 mm. In one embodiment, the user interface **37** is integral with the end effector **35**. In this embodiment, the end effector **35** includes one or more portions having a diameter suitable for gripping by the user. For example, a diameter of the proximal portion of the end effector **35** may be about 43 mm; a diameter of the distal portion of the end effector **35** may be about 36 mm; a diameter of the tool holder **51** may be about 19 mm; and a diameter of the tool **50** may be about 6 mm. In one embodiment, the distal portion of the end effector **35** includes a grip for the user's index finger. The interface **37** may optionally include a taper to accommodate users with different hand sizes. The interface **37** may also be shaped or contoured to mate with the contours of a user's hand and/or finger(s) and may include other ergonomic features, for example, to increase user comfort and prevent slippage (e.g., when the user's glove is wet/bloody).

[**0122**] One advantage of the haptic device **30** is that the user interface **37** advantageously enables the haptic device **30** to hold the tool **50** cooperatively with the user. In contrast, haptic devices used in surgical teleoperation systems have a "slave" device that exclusively holds the tool and a "master" device through which the surgeon controls the tool. The master device is typically remote from the surgical site either to permit the surgeon to perform the surgery over a distance or to provide a more ergonomic working position/environment for the surgeon. Thus, with a haptic teleoperation system, the surgeon has the disadvantage of having to rely entirely on the teleoperation system to view the surgical site and perform the surgery. In contrast, with the surgical system **10**, as user moves the tool **50** with guidance from the haptic device **30**, the user remains in close physical and visual proximity to the surgical site.

[**0123**] Another advantage of the haptic device **30** is that the haptic device **30** is not intended to move autonomously on its own. In contrast, autonomous surgical robotic systems used for orthopedic joint replacement perform bone cutting autonomously with a high speed burr. Although the surgeon monitors progress of the robot and may interrupt if necessary, the surgeon is not in full control of the procedure. With the haptic device **30**, however, the surgeon (as opposed to the robot) manipulates the tool **50**. Thus, the surgeon maintains control of the cutting operation and receives only guidance or assistance from the haptic device **30**. As a result,

the surgeon is not required to cede control to the robot of the haptic device **30**, which increases the surgeon's comfort level during the procedure.

[0124] As described above in connection with the computing system **20**, the haptic device **30** may include the computer **31**. The computer **31** may be housed in any convenient location on the surgical system **10**, such as, for example, on or in a stand or equipment cabinet (e.g., the platform **39** as shown in **FIG. 1**) on which the haptic device **30** is disposed. The computer **31** may be used in addition to or as an alternative to the computer **21** of the computing system **20**. The haptic device **30** (including the computer **31**) may also include any other computer, electronic, or electro-mechanical component suitable for use in a robotic and/or haptic device, such as, for example, a controller for receiving information from the encoders and redundant sensors on the arm **33**, amplifiers for providing power to the motors, clutches, brakes, a power supply for failsafe brakes, and/or a mode switch for placing the haptic device **30** in a desired operational mode (e.g., approach mode, haptic mode, free mode, input mode, hold mode).

[0125] The haptic device **30** is preferably sized so that the haptic device **30** can fit in an operating room without impeding other equipment or movement of the user about the operating room. For example, in one embodiment, a height of the haptic device **30** (with the arm **33** in a stored or retracted position) is approximately 1.4 m, and a footprint of the haptic device **30** is in a range of between about 0.25 m^2 to about 0.6 m^2. In another embodiment, the footprint is in a range of between about 0.09 m^2 and 0.13 m^2. Similarly, the haptic device **30** preferably has a weight that enables the haptic device **30** to be moved from one location to another with relative ease. For example, in one embodiment, the weight of the haptic device **30** is in a range of approximately 100 pounds to approximately 500 lbs. In another embodiment, the weight of the haptic device **30** is in a range of approximately 50 pounds to approximately 200 lbs. The haptic device **30** preferably has a low weight and small size both for ease of mobility and to permit the haptic device **30** to be optimally positioned for the surgical procedure. For example, the haptic device **30** (or any portion thereof) may be configured to rest on a floor of an operating room, to be mounted on the operating table (or other piece of equipment in the operating room), or to be affixed to a bone of the patient.

[0126] As shown in **FIG. 1**, the haptic device **30** (or a portion thereof, such as the robot) may be mounted on a platform **39**. The platform **39** may be any known platform, cart, or equipment stand, may include equipment racks and/or cabinets (e.g., to house the computer **31**), and is preferably configured to facilitate mobility of the haptic device **30**. For example, the platform **39** may include rolling members **38** (e.g., wheels or casters) to enable the platform **39** to be moved. The platform **39** may also include a mechanism for securing the platform **39** in position. For example, the platform **39** may be equipped with wheel locks or brakes for the rolling members **38**, a foot pedal locking device, jack stands, and/or any other known mechanism for securing a platform or cart in position. In one embodiment, as shown in **FIG. 2A**, the platform **39** includes rigid feet **39***a* that can be actuated between a retracted position (shown in **FIG. 2A**) and an extended position (not shown) with a mechanism **39***b*. To move the platform **39** from one location to another, the rigid feet **39***a* are retracted so that the platform **39** can travel on the rolling members **38**. To secure the platform **39** in position, the rigid feet **39***a* are extended so that the platform **39** rests on the rigid feet **39***a*. Alternatively, the rigid feet **39***a* could be fixed on the platform **39**, and the rolling members **38** could be extendable/retractable. Thus, the platform **39** enables the haptic device **30** to be moved from one location to another, positioned as necessary for each surgical case, and secured in a desired position during storage and surgery. Alternatively, the haptic device **30** (in whole or in part) may be installed in a room where a surgical procedure will be performed (e.g., mounted on a floor, wall, or workstation), integrated with the computing system **20**, integrated with an imaging device (e.g., a CT device, a fluoroscopic device, an ultrasound device, etc.), and/or integrated with a medical system (e.g., a medical equipment cart in a room where a surgical procedure will be performed).

[0127] As shown in **FIG. 1**, the haptic device **30** and the computing system **20** are preferably configured as separate units. Alternatively, the haptic device **30** (in whole or in part) and the computing system **20** (in whole or in part) may be integrated into a single unit. The haptic device **30** and the computing system **20** (or portions thereof) may also be integrated with other pieces of equipment, such as, for example, an imaging device (e.g., a CT device, an MRI device, a fluoroscopic device, an ultrasound device, etc.) and/or a hospital system (e.g., an equipment cart in a room where the surgical procedure will be performed). In one embodiment, the computer **21** and the computer **31** are disposed on the platform **39** of the haptic device **30**, and the display device **23** and the input device **25** of the computing system **20** are disposed on a light weight stand to facilitate the user's ability to view information from and input information to the surgical system **10**.

[0128] The tracking (or localizing) system **40** of the surgical system **10** is configured to determine a pose (i.e., position and orientation) of one or more objects during a surgical procedure to detect movement of the object(s). For example, the tracking system **40** may include a detection device that obtains a pose of an object with respect to a coordinate frame of reference of the detection device. As the object moves in the coordinate frame of reference, the detection device tracks the pose of the object to detect (or enable the surgical system **10** to determine) movement of the object. As a result, the computing system **20** can adjust the control parameters (e.g., by adjusting a virtual object) in response to movement of the tracked object. Tracked objects may include, for example, tools/instruments, patient anatomy, implants/prosthetic devices, and components of the surgical system **10**. Using pose data from the tracking system **40**, the surgical system **10** is also able to register (or map or associate) coordinates in one space to those in another to achieve spatial alignment or correspondence (e.g., using a coordinate transformation process as is well known). Objects in physical space may be registered to any suitable coordinate system, such as a coordinate system being used by a process running on the computer **21** and/or the computer **31**. For example, utilizing pose data from the tracking system **40**, the surgical system **10** is able to associate the physical anatomy and the tool **50** (and/or the haptic device **30**) with a representation of the anatomy (such as an image displayed on the display device **23**). Based on tracked object and registration data, the surgical system **10** may determine,

for example, (a) a spatial relationship between the image of the anatomy and the relevant anatomy and (b) a spatial relationship between the relevant anatomy and the tool **50** so that the computing system **20** can superimpose (and continually update) a virtual representation of the tool **50** on the image, where the relationship between the virtual representation and the image is substantially identical to the relationship between the tool **50** and the actual anatomy. Additionally, by tracking not only the tool **50** but also the relevant anatomy, the surgical system **10** can compensate for movement of the relevant anatomy during the surgical procedure (e.g., by adjusting a virtual object in response to the detected movement).

[**0129**] Registration may include any known registration technique, such as, for example, image-to-image registration (e.g., monomodal registration where images of the same type or modality, such as fluoroscopic images or MR images, are registered and/or multimodal registration where images of different types or modalities, such as MRI and CT, are registered); image-to-physical space registration (e.g., image-to-patient registration where a digital data set of a patient's anatomy obtained by conventional imaging techniques is registered with the patient's actual anatomy); and/or combined image-to-image and image-to-physical-space registration (e.g., registration of preoperative CT and MRI images to an intraoperative scene).

[**0130**] The tracking system **40** may be any tracking system that enables the surgical system **10** to continually determine (or track) a pose of the relevant anatomy of the patient and a pose of the tool **50** (and/or the haptic device **30**). For example, the tracking system **40** may comprise a non-mechanical tracking system, a mechanical tracking system, or any combination of non-mechanical and mechanical tracking systems suitable for use in a surgical environment. The non-mechanical tracking system may include an optical (or visual), magnetic, radio, or acoustic tracking system. Such systems typically include a detection device adapted to locate in predefined coordinate space specially recognizable trackable elements (or trackers) that are detectable by the detection device and that are either configured to be attached to the object to be tracked or are an inherent part of the object to be tracked. For example, the a trackable element may include an array of markers having a unique geometric arrangement and a known geometric relationship to the tracked object when the trackable element is attached to the tracked object. The known geometric relationship may be, for example, a predefined geometric relationship between the trackable element and an endpoint and axis of the tracked object. Thus, the detection device can recognize a particular tracked object, at least in part, from the geometry of the markers (if unique), an orientation of the axis, and a location of the endpoint within a frame of reference deduced from positions of the markers. The markers may include any known marker, such as, for example, extrinsic markers (or fiducials) and/or intrinsic features of the tracked object. Extrinsic markers are artificial objects that are attached to the patient (e.g., markers affixed to skin, markers implanted in bone, stereotactic frames, etc.) and are designed to be visible to and accurately detectable by the detection device. Intrinsic features are salient and accurately locatable portions of the tracked object that are sufficiently defined and identifiable to function as recognizable markers (e.g., landmarks, outlines of anatomical structure, shapes, colors, or any other sufficiently recognizable visual indicator). The markers may be located using any suitable detection method, such as, for example, optical, electromagnetic, radio, or acoustic methods as are well known. For example, an optical tracking system having a stationary stereo camera pair sensitive to infrared radiation may be used to track markers that emit infrared radiation either actively (such as a light emitting diode or LED) or passively (such as a spherical marker with a surface that reflects infrared radiation). Similarly, a magnetic tracking system may include a stationary field generator that emits a spatially varying magnetic field sensed by small coils integrated into the tracked object.

[**0131**] In one embodiment, as shown in **FIG. 1**, the tracking system **40** includes a non-mechanical tracking system. In this embodiment, the non-mechanical tracking system is an optical tracking system that comprises a detection device **41** and at least one trackable element (or tracker) configured to be disposed on (or incorporated into) a tracked object and detected by the detection device **41**. As shown in **FIG. 1**, the detection device **41** may include, for example, a stereo camera pair sensitive to infrared radiation and positionable in an operating room where the surgical procedure will be performed. The tracker is configured to be affixed to the tracked object in a secure and stable manner and includes an array of markers (e.g., an array S1 in **FIG. 4**) having a known geometric relationship to the tracked object. The markers may be active (e.g., light emitting diodes or LEDs) or passive (e.g., reflective spheres, a checkerboard pattern, etc.) and preferably have a unique geometry (e.g., a unique geometric arrangement of the markers) or, in the case of active, wired markers, a unique firing pattern. In operation, the detection device **41** detects positions of the markers, and the unique geometry (or firing pattern) and known geometric relationship to the tracked object enable the surgical system **10** to calculate a pose of the tracked object based on the positions of the markers.

[**0132**] Because the non-mechanical tracking system relies on an ability of the detection device **41** to optically "see" the markers, the detection device **41** and the tracker should be positioned so that a clear line of sight between the detection device **41** and the markers is maintained during the surgical procedure. As a safeguard, the surgical system **10** is preferably configured to alert a user if the detection device **41** is unable to detect the tracker during the procedure (e.g., when the line of sight between the detection device **41** and one or more of the markers is blocked and/or when reflectivity of the markers is occluded). For example, the surgical system **10** may include an audible (and/or visual) alarm programmed to sound (and/or flash) when a person steps between the markers and the detection device **41**, when an object is interposed between the markers and the detection device **41**, when a lens of the camera is occluded (e.g., by dust), and/or when reflectivity of the markers is occluded (e.g., by blood, tissue, dust, bone debris, etc.). The surgical system **10** may also include programming to trigger other safety features, such as, for example, an occlusion detection algorithm (discussed below in connection with step S11 of **FIG. 13**) with a power shutoff feature that disables the tool **50** when the detection device **41** loses sight of the markers.

[**0133**] The non-mechanical tracking system may include a trackable element (or tracker) for each object the user desires to track. For example, in one embodiment, the non-mechanical tracking system includes an anatomy tracker **43** (to track

patient anatomy), a haptic device tracker **45** (to track a global or gross position of the haptic device **30**), an end effector tracker **47** (to track a distal end of the haptic device **30**), and an instrument tracker **49** (to track an instrument/tool held manually by the user).

[**0134**] As shown in **FIG. 1**, the anatomy tracker **43** is disposed on a relevant portion of a patient's anatomy (such as a bone) and is adapted to enable the relevant anatomy to be tracked by the detection device **41**. The anatomy tracker **43** includes a fixation device for attachment to the anatomy. The fixation device may be, for example, a bone pin, surgical staple, screw, clamp, wearable device, intramedullary rod, or the like. In one embodiment, the anatomy tracker **43** is configured for use during knee replacement surgery to track a femur F and a tibia T of a patient. In this embodiment, as shown in **FIG. 1**, the anatomy tracker **43** includes a first tracker **43***a* adapted to be disposed on the femur F and a second tracker **43***b* adapted to be disposed on the tibia T. As shown in **FIG. 4**, the first tracker **43***a* includes a fixation device comprising bone pins P and a unique array S**1** of markers (e.g., reflective spheres). The array S**1** is affixed to a connection mechanism **400** that is adapted to be removably secured to both of the bone pins P. For example, as shown in **FIG. 4**, the connection mechanism **400** may include a first portion **442**, a second portion **444**, and screws **445**. To install the first tracker **43***a* on the femur F, the user screws the bone pins P into the femur F, slides the connection mechanism **400** over the bone pins P, and tightens the screws **445** to draw the first and second portions **442** and **444** together to thereby securely fix the connection mechanism **400** to the bone pins P. Once secured, the connection mechanism **400** imparts additional stability to the bone pins P. The second tracker **43***b* is identical to the first tracker **43***a* except the second tracker **43***b* is installed on the tibia T and has its own unique array of markers. When installed on the patient, the first and second trackers **43***a* and **43***b* enable the detection device **41** to track motion of the femur F and the tibia T during knee replacement surgery. As a result, the surgical system **10** is able to compensate for bone motion in real-time during surgery.

[**0135**] As shown in **FIG. 2A**, the haptic device tracker **45** is disposed on the haptic device **30** and is adapted to enable the surgical system **10** to monitor a global or gross position of the haptic device **30** in physical space. In particular, the haptic device tracker **45** enables the surgical system **10** to determine whether the haptic device **30** has moved relative to other objects in the surgical environment, such as the patient. Such information is important because the tool **50** is attached to the haptic device **30**. For example, if the user intentionally repositions or inadvertently bumps the haptic device **30** while cutting the femur F with the tool **50**, the tracking system **40** will detect movement of the haptic device tracker **45**. In response, the surgical system **10** can make appropriate adjustments to programs running on the computer **21** and/or the computer **31** to compensate for global or gross movement of the haptic device **30** (and the attached tool **50**) relative to the femur F. As a result, integrity of the femur preparation process is maintained.

[**0136**] As shown in **FIGS. 2A and 5**, the haptic device tracker **45** includes a unique array S**3** of markers (e.g., reflective spheres) and is adapted to be mounted on the base **32** of the haptic device **30**. The haptic device tracker **45** is preferably mounted so that the haptic device tracker **45** can be secured in a fixed position relative to the base **32**. The fixed position is calibrated to the haptic device **30** (as discussed below in connection with step S**9** of **FIG. 13**) so that the surgical system **10** knows where the haptic device tracker **45** is located with respect to the base **32** of the haptic device **30**. Once calibrated, the fixed position is maintained during the surgical procedure. In one embodiment, as shown in **FIGS. 2A and 5**, the haptic device tracker **45** includes an arm **34** having a proximal end connected to the base **32** (e.g., via screws, rivets, welding, clamps, magnets, etc.) and a distal end that carries the array S**3** of markers. The arm **34** may include one or more support members (e.g., brackets, struts, links, etc.) having a rigid structure so that the haptic device tracker **45** is fixed in a permanent position with respect to the haptic device **30**. Preferably, however, the arm **34** is adapted for adjustability so that the array S**3** is moveable between a first position and a second position relative to the haptic device **30**. Thus, the array S**3** may be positioned independently of the base **32** of the haptic device **30** before being secured in a fixed position. One advantage of adjustability is that a position of the array S**3** may be customized for each surgical case (e.g., based on patient size, operating table height, etc.). Another advantage of adjustability is that the array S**3** may be positioned so as not to impede the user during a surgical procedure. Adjustability may be imparted to the arm **34** in any known manner (e.g., an articulating arm, a flexible neck, etc.). For example, in one embodiment, as shown in **FIG. 5**, the arm **34** includes a ball joint **34***b* on which the haptic device tracker **45** is disposed. The ball joint **34***b* includes a locking mechanism actuated by a handle **34***a*. In operation, the user may unscrew the handle **34***a* to release the ball joint **34***b*, manipulate the ball joint **34***b* until the haptic device tracker **45** is in a desired position, and tighten the handle **34***a* until the ball joint **34***b* is fixedly secured. In this manner, the haptic device tracker **45** may be fixed in the desired position. As an alternative to securing the haptic device tracker **45** in a fixed position and calibrating the fixed position to the haptic device **30**, the arm **34** may include position sensors (e.g., encoders). The position sensors may be similar to the position sensors of the arm **33** and may operate in conjunction with appropriate software (e.g., software running on the computer **21** or the computer **31**) to provide measurements of a pose of the arm **34** relative to the base **32**. When position sensors are incorporated into the arm **34**, the calibration process of step S**11** below may be eliminated because the surgical system **10** can determine the location of the haptic device tracker **45** with respect to the base **32** based on the pose of the arm **34** provided by the position sensors.

[**0137**] The end effector tracker **47** is adapted to enable the surgical system **10** to determine a pose of a distal end (e.g., a working end) of the haptic device **30**. The end effector tracker **37** is preferably configured to be disposed on a distal end of the arm **33** or on the tool **50**. For example, as shown in **FIG. 6B**, the end effector tracker **47** may be disposed on the end effector **35**. As shown in **FIG. 6A**, the end effector tracker **47** may include a unique array S**4** of markers (e.g., reflective spheres) and may be adapted to be affixed to the end effector **35** in any known manner, such as, for example, with a clamping device, threaded connection, magnet, or the like. As shown in **FIG. 6A**, in one embodiment, the end effector tracker **47** is affixed to the end effector **35** with a clamp **1500**. The clamp **1500** may be formed integrally with the array S**4** or affixed to the array S**4** in any conventional

manner, such as with mechanical hardware, adhesive, welding, and the like. The clamp **1500** includes a first portion **1505**, a second portion **1510**, and a thumbscrew **1515**. The first and second portions **1505** and **1510** are shaped to receive a portion of the end effector, such as a cylindrical portion of the tool **50** or the tool holder **51**. For example, as shown in **FIG. 6A**, the first portion **1505** may have a planar surface and the second portion **1510** may have a V-shaped groove so that the first and second portions **1505** and **1510** can securely receive the tool **50** or the tool holder **51** when tightened together. To install the end effector tracker **47** on the end effector **35**, the first and second portions **1505** and **1515** of the clamp **1500** are disposed around the tool **50** or the tool holder **51** and tightened together using the thumbscrew **1515**. The end effector tracker **47** may also include a feature to aid in properly orienting the end effector tracker **47** when installing the end effector tracker **47** on the haptic device **30**. For example, the end effector tracker **47** may include a divot **47***a* as shown in **FIG. 6B**.

[**0138**] In one embodiment, the end effector tracker **47** is used only during calibration of the haptic device **30** (as discussed below in connection with step S**9** of **FIG. 13**) and is removed prior to performance of the surgical procedure. In this embodiment, the end effector tracker **47** is disposed on the end effector **35** (as shown in **FIG. 6B**) and the haptic device tracker **45** is mounted to the base **32** of the haptic device **30** (e.g., via the adjustable arm **34** as shown in **FIG. 2A**) so that a position of the haptic device tracker **45** with respect to the haptic device **30** is adjustable. Because the position of the haptic device tracker **45** is adjustable (as opposed to permanently fixed), the surgical system **10** does not know the location of the haptic device tracker **45** with respect to the haptic device **30**. To determine the geometric relationship between the haptic device **30** and the haptic device tracker **45**, the calibration process utilizes the end effector tracker **47**. Although the end effector tracker **47** may remain on the haptic device **30** for the entire surgical procedure (or any portion thereof), it is advantageous to remove the end effector tracker **47** when the calibration process is complete. For example, the user may desire to remove the end effector tracker **47** to prevent the tracker **47** from interfering with the user's grip on the haptic device **30**, the patient's anatomy, medical instruments and equipment, and/or other personnel in the operating room. Another advantage of removing the end effector tracker **47** is that movement of the end effector tracker **47** during the surgical procedure may result in degraded performance of the surgical system **10** due to delays or limited bandwidth as the tracking system **40** measures the movement end effector tracker **47**.

[**0139**] In an alternative embodiment, the end effector tracker **47** may be eliminated. In this embodiment, the haptic device tracker **45** is fixed in a permanent position on the haptic device **30**. Because the haptic device tracker **45** is fixed in a permanent position on the haptic device **30**, the relationship between the haptic device tracker **45** and the coordinate frame of the haptic device **30** is known. Accordingly, the surgical system **10** does not need the end effector tracker **47** for calibration to establish a relationship between the haptic device tracker **45** and the coordinate frame of the haptic device **30**. In this embodiment, the haptic device tracker **45** may be rigidly mounted on the haptic device **30** in any position that permits the tracking system **40** to see the array S**3** of the haptic device tracker **45**, that is close enough to the surgical site so as not to degrade accuracy, and that will not hinder the user or interfere with other personnel or objects in the surgical environment.

[**0140**] In another alternative embodiment, the haptic device **30** is firmly locked in position. For example, the haptic device **30** may be bolted to a floor of the operating room or otherwise fixed in place. As a result, the global or gross position of the haptic device **30** does not change substantially so the surgical system **10** does not need to track the global or gross position of the haptic device **30**. Thus, the haptic device tracker **45** may be eliminated. In this embodiment, the end effector tracker **47** may be used to determine an initial position of the haptic device **30** after the haptic device **30** is locked in place.

[**0141**] In another alternative embodiment, the tracking system **40** is attached to the haptic device **30** in a permanently fixed position. For example, the tracking system **40** (including the detection device **41**) may be mounted directly on the haptic device **30** or connected to the haptic device **30** via a rigid mounting arm or bracket so that the tracking system is fixed in position with respect to the haptic device **30**. In this embodiment, the haptic device tracker **45** and the end effector tracker **47** may be eliminated because a position of the tracking system **40** relative to the haptic device **30** is fixed and may be established during a calibration procedure performed, for example, during manufacture or set up of the haptic device **30**.

[**0142**] In another alternative embodiment, the tracking system **40** is attached to the haptic device **30** in an adjustable manner. For example, the tracking system **40** (including the detection device **41**) may be connected to the haptic device **30** with an arm, such as the adjustable arm **34** (described above in connection with the haptic device tracker **45**) so that the tracking system **40** is moveable from a first position to a second position relative to the haptic device **30**. After the arm and the tracking system **40** are locked in place, a calibration can be performed to determine a position of the tracking system **40** relative to the haptic device **30**. The calibration may be performed, for example, using the end effector tracker **47**.

[**0143**] The instrument tracker **49** is adapted to be coupled to an instrument **150** that is held manually in the hand of the user (as opposed, for example, to the tool **50** that is attached to the end effector **35**). The instrument **150** may be, for example, a probe, such as a registration probe (e.g., a straight or hooked probe). As shown in **FIG. 7**, the instrument tracker **49** may comprise a unique array S**5** of markers (e.g., reflective spheres) formed integrally with the instrument **150** or affixed to the instrument **150** in any known manner, such as with mechanical hardware, adhesive, welding, a threaded connection, a clamping device, a clip, or the like. When the instrument tracker **49** is removably connected to the instrument **150**, such as with a clip or a clamping device, the instrument tracker **49** should be calibrated to the instrument **150** to determine a relationship between the instrument tracker **49** and a geometry of the instrument **150**. Calibration may be accomplished in any suitable manner, such as with a tool calibrator having a divot or a V-groove (e.g., as described in U.S. Patent Application Pub. No. US 2003/0209096, which is hereby incorporated by reference herein in its entirety). One advantage of using a clip or clamping device (such as the clamp **1500** shown in **FIG. 6A**)

to connect the tracker **49** to the instrument **150** is that the clip or clamping device may be adjustable to fit various sizes of instruments. Thus, a single clip or clamping device may be used with multiple instruments. Knowing a geometric relationship between the array S**5** and the instrument **150**, the surgical system **10** is able to calculate a position of a tip of the instrument **150** in physical space. Thus, the instrument **150** can be used to register an object by touching a tip of the instrument **150** to a relevant portion of the object. For example, the instrument **150** may be used to register a bone of the patient by touching landmarks on the bone or points on a surface of the bone. The instrument **150** may also be used to verify proper alignment of an implant installed in the patient by touching the tip of the instrument **150** to predefined verification features (e.g., divots) located on the implant.

[**0144**] The instrument tracker **49** may also be configured to verify calibration of the instrument **150**. For example, another tracker (e.g., the tracker **43**, **45**, or **47**) may include a divot into which the user can insert the tip of the instrument **150**. In one embodiment, as shown in **FIG. 6B**, the end effector tracker **47** includes a divot **47***a* into which the user can insert the tip of the instrument **150**. The detection device **41** can then acquire pose data for the instrument tracker **49** and the end effector tracker **47**, and the surgical system **10** can compare an actual geometric relationship between the trackers **47** and **49** to an expected geometric relationship. Deviation between the actual and expected geometric relationships indicates that a physical parameter (e.g., straightness, tip position, etc.) of the instrument **150** is out of calibration. As shown in **FIG. 29**, during the verification process, the surgical system **10** may display a screen showing a graphical representation of the instrument **150**, the instrument tracker **49**, and the end effector tracker **47** on the display device **23**.

[**0145**] The tracking system **40** may additionally or alternatively include a mechanical tracking system. In contrast to the non-mechanical tracking system (which includes a detection device **41** that is remote from the trackers **43**, **45**, **47**, and **49**), a mechanical tracking system may be configured to include a detection device (e.g., an articulating arm having joint encoders) that is mechanically linked (i.e., physically connected) to the tracked object. The tracking system **40** may include any known mechanical tracking system, such as, for example, a mechanical tracking system as described in U.S. Pat. No. 6,033,415 and/or U.S. Pat. No. 6,322,567, each of which is hereby incorporated by reference herein in its entirety. In one embodiment, the tracking system **40** includes a mechanical tracking system having a jointed mechanical arm **241** (e.g., an articulated arm having six or more degrees of freedom) adapted to track a bone of the patient. As shown in **FIG. 8**, the arm **241** has a proximal end affixed to the base **32** of the haptic device **30** and a freely moveable distal end fixed to the femur F of the patient. Alternatively, the proximal end may be affixed to any other suitable location (such as, for example, to a rail of an operating table, a leg holder, etc.) but is preferably connected (e.g., directly or via a bracket) to the base **32** of the haptic device **30** so that the arm **241** moves globally with the haptic device **30**. The distal end of the arm **241** includes an fixation device **245** adapted for rigid fixation to the femur F, such as, for example, a bone pin, bone screw, clamp, wearable device, surgical staple, or the like. The arm **241** is configured to have multiple degrees of freedom. For example, in one embodiment, as shown in **FIG. 8**, the arm **241** includes a plurality of links **242** connected at joints **244**. Each joint **244** incorporates one or more position sensors (not shown) to track a pose of the arm **241**. The position sensors may include any suitable sensor, such as, for example, the position sensors described above in connection with the arm **33** of the haptic device **30**. In operation, as the femur F moves, the distal end of the arm travels with the femur F. The position sensors (and appropriate software) produce measurements of a pose of the distal end of the arm relative to the proximal end of the arm fixed to the haptic device **30**. In this manner, motion of the femur F relative to the haptic device **30** is captured. The mechanical tracking system **240** may also include a second arm that is identical to the arm **241** but is rigidly affixed to the tibia T to enable the tracking system **240** to track motion of the tibia T. In this manner, the mechanical tracking system **240** may be used to track the femur F and the tibia T so that the surgical system **10** can detect bone motion in real time during surgery. Using bone motion data in conjunction with appropriate software, the surgical system **10** can compensate for the bone motion in real time during surgery.

[**0146**] One advantage of the mechanical tracking system over a non-mechanical tracking system is that the detection device (i.e., the arm **241**) is physically connected to the tracked object and therefore does not require a line of site to "see" markers on the tracked object. Thus, the user and other personnel may freely move about the operating room during a surgical procedure without worrying about blocking an invisible line of sight between a set of markers and an optical camera. Another advantage of the mechanical tracking system is that the arm **241** may be physically connected to the haptic device **30** (e.g., to the base **32**). Such a configuration eliminates the need to track a global or gross position of the haptic device **30** relative to the patient (e.g., using the haptic device tracker **45** as described above). There is no need to track the global or gross position of the haptic device **30** because the arm **241** moves with the haptic device **30**. As a result, the haptic device **30** may be repositioned during a procedure without having to be recalibrated to a bone motion tracking system. Additionally, mechanical tracking systems may be more accurate than non-mechanical tracking systems and may enable faster update rates to the computer **21** and/or the computer **31**. Faster update rates are possible because a mechanical tracking system is hardwired to the computer **21** and/or the computer **31**. Thus, the update rate is limited only by the speed of the computer **21** and/or the computer **31**.

[**0147**] In an alternative embodiment, the arm **241** of the mechanical tracking system may be attached to an operating table, a leg holder **62** (e.g., as shown in **FIG. 14A**), or other structure in the surgical environment. In this embodiment, a calibration is performed to determine a pose of the arm **241** relative to the haptic device **30**. For example, in one embodiment, the calibration is performed by placing the distal end (e.g., the end effector **35**) of haptic device **30** in a known geometric relationship with the distal end of the arm **241**. In another embodiment, the distal end of the arm **241** is placed in a known geometric relationship with the base **32** of the haptic device **30**. In yet another embodiment, the distal end (e.g., the end effector **35**) of the haptic device **30** is brought into a known geometric relationship with a base of the arm **241**.

[0148] When the tracking system **40** includes the mechanical tracking system, the arm **241** may be used to register the patient's anatomy. For example, the user may use the arm **241** to register the tibia T while the second arm (i.e., the arm that is identical to the arm **241** but that is affixed to the tibia T) tracks motion of the tibia T. Registration may be accomplished, for example, by pointing a tip of the distal end of the arm **241** to anatomical landmarks on the tibia T and/or by touching points on (or "painting") a surface of the tibia T with the tip of the distal end of the arm **241**. As the user touches landmarks on the tibia T and/or paints a surface of the tibia T, the surgical system **10** acquires data from the position sensors in the arm **241** and determines a pose of the tip of the arm **241**. Simultaneously, the second arm provides data regarding motion of the tibia T so that the surgical system **10** can account for bone motion during registration. Based on the bone motion data and knowledge of the position of the tip of the arm **241**, the surgical system **10** is able to register the tibia T to the diagnostic images and/or the anatomical model of the patient's anatomy in the computing system **20**. In a similar manner, the second arm may be used to register the femur F while the arm **241** (which is affixed to the femur F) tracks motion of the femur F. The patient's anatomy may also be registered, for example, using a non-mechanical tracking system in combination with a tracked probe (e.g., the instrument **150** with the instrument tracker **49**) and/or using the haptic device **30** (e.g., as described below in connection with step S**8** of **FIG. 13**).

[0149] As shown in **FIG. 1**, the tracking system **40** may be coupled to the haptic device **30** via an interface **100***b*. The interface **100***b* includes a physical interface and a software interface. The physical interface may be any known interface such as, for example, a wired interface (e.g., serial, USB, Ethernet, CAN bus, and/or other cable communication interface) and/or a wireless interface (e.g., wireless Ethernet, wireless serial, infrared, and/or other wireless communication system). The software interface may be resident on the computer **21** and/or the computer **31** and enables the haptic device **30** and the computing system **20** to communicate with and control operation of the tracking system **40**.

[0150] The surgical system **10** is adapted to be connected to a power source. The power source may be any known power source, such as, for example, an electrical outlet, a battery, a fuel cell, and/or a generator and may be connected to the surgical system **10** using conventional hardware (e.g., cords, cables, surge protectors, switches, battery backup/UPS, isolation transformer, etc.). The surgical system **10** preferably includes a user-activated device for manually controlling a supply of power to the tool **50**. For example, the surgical system **10** may include a foot pedal (or other switching device) that can be positioned on the floor of the operating room in proximity to the user. Depressing the foot pedal causes the power source to supply power to the tool **50** (or to a compressed air supply in the case of a pneumatic tool **50**). Conversely, releasing the foot pedal disrupts the flow of power to the tool **50**. The surgical system **10** may also be adapted to automatically disrupt the flow of power to the tool **50** to promote safety. For example, the surgical system **10** may include programs or processes (e.g., running on the computer **21** and/or the computer **31**) configured to shut off the tool **50** if a dangerous condition is detected, such as, for example, when the anatomy tracker **43** and/or the haptic device tracker **45** become occluded during a critical operation such as bone cutting.

[0151] In operation, the computing system **20**, the haptic device **30**, and the tracking system **40** cooperate to enable the surgical system **10** to provide haptic guidance to the user during a surgical procedure. The surgical system **10** provides haptic guidance by simulating the human tactile system using a force feedback haptic interface (i.e., the haptic device **30**) to enable the user to interact with a virtual environment. The haptic device **30** generates computer controlled forces to convey to the user a sense of natural feel of the virtual environment and virtual (or haptic) objects within the virtual environment. The computer controlled forces are displayed (i.e., reflected or conveyed) to the user to make him sense the tactile feel of the virtual objects. For example, as the user manipulates the tool **50**, the surgical system **10** determines the position and orientation of the tool **50**. Collisions between a virtual representation of the tool **50** and virtual objects in the virtual environment are detected. If a collision occurs, the surgical system **10** calculates haptic reaction forces based on a penetration depth of the virtual tool into the virtual object. The calculated reaction forces are mapped over the virtual object surface and appropriate force vectors are fed back to the user through the haptic device **30**. As used herein, the term "virtual object" (or "haptic object") can be used to refer to different objects. For example, the virtual object may be a representation of a physical object, such as an implant or surgical tool. Alternatively, the virtual object may represent material to be removed from the anatomy, material to be retained on the anatomy, and/or anatomy (or other objects) with which contact with the tool **50** is to be avoided. The virtual object may also represent a pathway, a guide wire, a boundary, a border, or other limit or demarcation.

[0152] To enable the user to interact with the virtual environment, the surgical system **10** employs a haptic rendering process. One embodiment of such a process is represented graphically in **FIG. 40**. In operation, position sensors (block **2502**) of the haptic device **30** (block **2500**) provide data to a forward kinematics process (block **2504**). Output of the forward kinematics process is input to a coordinate transformation process (block **2506**). A haptic rendering algorithm (block **2508**) receives data from the coordinate transformation process and provides input to a force mapping process (block **2510**). Based on the results of the force mapping process, actuators (block **2512**) of the haptic device **30** are actuated to convey an appropriate haptic wrench (i.e., force and/or torque) to the user. The position sensors of block **2502** and the actuators of block **2512** are described above in connection with the arm **33** of the haptic device **30**. The forward kinematics process of block **2504** and the coordinate transform process of block **2506** are discussed below in connection with step S**708** of **FIG. 43**. The haptic rendering algorithm of block **2508** and the force mapping process of block **2510** are discussed below in connection with **FIG. 50**.

[0153] The haptic rendering process may include any suitable haptic rendering process, such as, for example, a haptic rendering process as described in U.S. Pat. No. 6,111,577; C. B. Zilles & J. K. Salisbury, *A constraint-based god-object method for haptic display*, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol. 3, pp. 146-51, 1995; T. V. Thompson II, D. E. Johnson & E. Cohen, *Direct haptic rendering of sculptured models*, Proceedings of the Symposium on Interactive 3D Graphics, pp. 167-76, 1997; K. Salisbury & C.

Tar, *Haptic rendering of surfaces defined by implicit functions*, Proceedings of the ASME Dynamic Systems and Control Division, DSC-Vol. 61, pp. 61-67, 1997; and/or J. E. Colgate, M. C. Stanley & J. M. Brown, *Issues in the haptic display of tool use*, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol. 3, pp. 140-45, 1995, each of which is hereby incorporated by reference herein in its entirety.

[0154] The virtual environment created by the haptic rendering process includes virtual (or haptic) objects that interact with a virtual representation of the tool **50**. Interaction between the virtual objects and the virtual representation of the tool **50** may be point-based or ray-based. In a preferred embodiment, the surgical system **10** employs point-based haptic interaction where only a virtual point, or haptic interaction point (HIP), interacts with virtual objects in the virtual environment. The HIP corresponds to a physical point on the haptic device **30**, such as, for example, a tip of the tool **50**. The HIP is coupled to the physical point on the physical haptic device **30** by a virtual spring/damper model. The virtual object with which the HIP interacts may be, for example, a haptic object **705** (shown in **FIG. 42**) having a surface **707** and a haptic force normal vector F_n. A penetration depth d_i is a distance between the HIP and the nearest point on the surface **707**. The penetration depth d_i represents the depth of penetration of the HIP into the haptic object **705**.

[0155] The virtual (or haptic) objects can be modeled, for example, using 3D geometric primitive objects, 3D polygonal objects, mathematical equations, computer models, surface models, and/or voxel arrays. Haptic objects may be static, quasi-static, dynamic, continuous, discontinuous, time varying, and/or existing only at certain times. In one embodiment, the haptic object is modeled using one or more functions of tool position, orientation, velocity, and/or acceleration. Thus, in the case of a surgical bone cutting operation, the haptic rendering process may produce a mapping of output wrench versus tool position. The mapping may be configured so that the output wrench fed back to the user is sufficient to resist further penetration of the virtual tool (or HIP) into the haptic object. In this manner, a virtual cutting boundary is established. The virtual boundary is associated with (e.g., registered to) the physical anatomy of the patient, an image of the anatomy, and/or other coordinate frame of interest. A haptic object rendered by the haptic rendering process may function as a pathway (e.g., a guide wire), may be repulsive (e.g., configured to repel the tool **50** from entering an interior of a haptic object), may function as a container (e.g., to maintain the tool **50** within the interior of the haptic object), and/or may have portions that repel and portions that contain. As shown in **FIG. 41**, multiple haptic objects **701** may be superimposed so that force vectors F from each of the haptic objects **701** are combined to yield a resultant haptic force vector F_v. In one embodiment, the output from each haptic object **701** comprises a Cartesian force vector with respect to an inertial coordinate frame and having linear properties. The maximum number of haptic objects may be determined based on computational costs.

[0156] A haptic object may be customized to include any desired shape, such as, for example, anatomically contoured implant shapes, protective boundaries for sensitive structures (e.g., intra-articular anatomy), image-derived tumor boundaries, and virtual fixtures for in vivo assembly of implant components. In one embodiment, the haptic object may be uniquely contoured to match a disease state of the patient. For example, the haptic object may define a virtual cutting boundary that encompasses only diseased bone. Thus, the haptic object can be used to guide the user in removing the diseased bone while sparing healthy surrounding bone. In this manner, the surgical system **10** enables the user to sculpt bone in a customized manner, including complex geometries and curves that are not possible with conventional cutting jigs and saw guides. As a result, the surgical system **10** facilitates bone sparing surgical procedures and implant designs that are smaller in size and adapted for a patient's unique disease state.

[0157] A haptic object may have an associated spatial or geometric representation that can be graphically represented on the display device **23**. The graphical representation may be selected so as to convey useful information to the user. For example, as shown in **FIG. 1**, a haptic object **300** configured assist the user in guiding the tool **50** to the surgical site may be represented graphically as a funnel shaped volume. As a virtual tool corresponding to the physical tool **50** moves through and interacts with the haptic object **300**, haptic forces are reflected to the user so that the tool **50** is directed to the surgical site. Alternatively, as shown in **FIG. 9**, a haptic object **310** may be represented graphically as a guide wire. As the virtual tool moves along and interacts with the haptic object **310**, haptic forces are reflected to the user so that the tool **50** is guided directly to the surgical site. In one embodiment, a haptic object defining a virtual cutting boundary for an implant may be depicted on the display device **23** as a graphical image having a shape that substantially corresponds to a shape of the implant. Thus, a haptic object **208** defining a virtual cutting boundary for a femoral component **72** (shown in **FIG. 10A**) may have a corresponding graphical representation as shown in **FIG. 9**. Similarly, a haptic object **206** defining a virtual cutting boundary for a tibial component **74** (shown in **FIG. 10B**) may have a corresponding graphical representation as shown in **FIG. 9**.

[0158] Haptic objects having simple volumes are preferably modeled with a combination of 3D implicit surface objects such as planes, spheres, cones, cylinders, etc. For example, the haptic object **705** shown in **FIG. 42** is a sphere. Surfaces of the haptic object **705** are continuously smooth, and solutions to the penetration depth d_i and the haptic force normal vector F_n can be obtained at a non-expensive, fixed computational cost from compact mathematical surface functions based on the haptic interaction point (HIP). For more complex objects, polygon based haptic rendering techniques may be used.

[0159] **FIG. 43** illustrates an embodiment of a polygon based haptic rendering process according to the present invention. In step S**702**, a virtual environment with which the user can interact is generated using, for example, computer-aided design (CAD) software. The virtual environment may be created, for example, using an explicit surface model. In one embodiment, the virtual environment includes a 3D virtual (or haptic) object comprising multiple polygonal surface objects. As shown in **FIG. 44**, each surface object is preferably triangular and represented by three nodes (or vertices) v**0**, v**1**, and v**2** and a normal vector n. The virtual object can be re-shaped to compensate for a physical diameter of the tool **50**, for example, by offsetting the walls

of the virtual object by a radius of the tool **50**. To improve computational performance, which is important in real-time applications, the polygonal surface objects can be re-meshed, for example, to eliminate polygons smaller than a desired spatial resolution. When the virtual object is a closed cavity, creation of the virtual object using a CAD system may be simplified by generating the virtual object with two surfaces: an outer object surface and an inner cavity surface. Using only the inner cavity surface, however, may advantageously reduce the required volume for rendering and the number of polygonal objects (e.g., triangles, polygons, etc.). In one embodiment, the rendering process can support uni-directional entrance behavior to a closed virtual object, where the HIP is permitted to pass through the virtual object only if it is moving from outside to inside.

[**0160**] In step S**704** of **FIG. 43**, the haptic rendering process creates a voxel map of the polygonal surface objects in the virtual environment. To create the voxel map, the virtual objects in the virtual environment are spatially partitioned into smaller cells (voxels) to reduce the number of polygonal surface objects and avoid unnecessary collision detection checks. As shown in **FIG. 45**, the virtual objects are segmented into an $n_i \times n_j \times n_k$ grid. The grid may be regularly spaced or may vary in resolution. Each voxel has a pointer to the polygons that occupy or intersect the voxel. Given a set of polygons, a voxel lookup table is constructed by the following steps: retrieve the polygon data (i.e., the xyz components for the vertices v**0**, v**1**, and v**2**) for a polygon of interest; create a bounding box around the polygon; add a unique identity number for the polygon to the voxels that are within the bounding box; and increase the total number of polygons occupying the voxel. These steps are repeated until the last polygon is processed. As shown in **FIG. 44** (poly reference frame) and **FIG. 45** (voxel reference frame), a point p in the poly frame is converted into the voxel frame using the formula v_{ijk}=(int)floor(p/s), where s is voxel size. Examples of voxel and polygon lookup tables are presented in **FIGS. 46A and 46B**, respectively.

[**0161**] In step S**706** of **FIG. 43**, the haptic rendering process creates a guide line to a target point or a target region. The guide line functions as a pathway or guide wire that guides the HIP to a particular location. A guide line is useful, for example, to guide the user's movement of the physical tool **50** so that the tool **50** avoids critical anatomy. A guide line is also useful with a closed haptic volume that the user is unable to traverse. Implementation of a guide line is explained with reference to **FIG. 47**, which illustrates a virtual sphere **720**. The sphere **720** includes an active zone defined by a center and a radius of the sphere **720**. When the HIP is outside the active zone, the user can freely move the haptic device **30**. When the HIP enters the active zone, the haptic device **30** is placed in an approach mode in which a guiding line segment **722** is created. The guiding line segment **722** extends, for example, from an entering point **723** on a surface of the sphere **720** to a target point **721** (e.g., a target point pair {pe, pt}). Normally, the center of the sphere **720** will be coincident with the target point (or will be within a target region). When the guiding line segment **722** is activated, the HIP can move freely along the guiding line segment **723**. Motion of the HIP that deviates from the guiding line segment **722** (e.g., motion perpendicular to the guiding line segment **722**), results in a resisting force that is fed back to the user. As the HIP approaches the target point, a distance from a current location of the HIP to the target point is monitored. When the distance is smaller than a confine radius, the behavior of the HIP is restricted, for example, by implementing a uni-directionally constrained virtual confining sphere **724**. A radius of the confining sphere **724** is reduced as the HIP moves closer to the target point. When the distance from the HIP to the target point is smaller than a switch radius (represented in **FIG. 47** by a switch sphere **725**), haptic rendering of the virtual object begins.

[**0162**] In step S**708** of **FIG. 43**, the haptic rendering process maps the physical HIP (e.g., the tip of the tool **50**) to virtual space. For example, the forward kinematics process (block **2504**) of **FIG. 40** computes a Cartesian position of the physical HIP with respect to an inertial reference frame Ri. The coordinate transformation process (block **2506**) of **FIG. 40** performs coordinate transformations between the inertial reference frame Ri, a poly frame Rp (a reference frame attached to a polygonal virtual object), and a voxel frame Rv (a reference frame attached to a voxel array) as illustrated in **FIG. 48**. Once the haptic rendering process has determined the position of the HIP with respect to the poly frame Rp, the haptic rendering process proceeds to step S**710** and searches candidate polygonal objects by looking at occupied voxels and neighboring voxels. In step S**712**, the haptic rendering process checks for a collision (e.g., the HIP has passed through a polygonal object since the last rendering cycle) and determines a virtual proxy point location (e.g., a constrained location of the HIP along a surface of the virtual object) based on desired virtual proxy behaviors (as described below in connection with **FIG. 49**). In step S**714**, desired stiffness and damping matrices that are predefined in tool coordinates are transformed into inertial reference frame coordinates. In step S**716**, a haptic force to be fed back to the user through the haptic device **30** is computed based on a desired hardness of a virtual surface defined by the virtual spring and damping force that couples the HIP to the haptic device **30**. In step S**718**, the computed haptic force is displayed or reflected to the user through the haptic device **30**.

[**0163**] As shown in **FIGS. 49A and 49B**, a location of an initial virtual proxy point may be determined based on a location HIP(t) of the HIP at a current time t and a location HIP(t−1) of the HIP at a previous time t−1. For example, when the HIP is outside a virtual object, the haptic rendering process checks for an initial contact between the HIP and a surface of the virtual object by detecting an intersection between the polygonal surface objects that comprise the virtual object and a line segment L extending between the locations HIP(t) and HIP(t−1). A location VP(t) of the initial virtual proxy point is computed as the intersecting point of the line segment L and the polygonal surface objects.

[**0164**] **FIG. 50** shows a flowchart detailing an embodiment of a haptic rendering algorithm (block **2508** of **FIG. 40**) based on polygonal surface objects according to the present invention. In step S**100**, the position of HIP(t) is updated and transformed to the poly reference frame. In step S**101**, the algorithm determines whether collisionDetectedFlag(t−1) has a value of 1. If not, in step S**103**, the algorithm maps the HIP(t) into voxel coordinates. In step S**105**, the algorithm determines whether the HIP(t) is inside a voxel bounding box. If not, no collision is detected, and the algorithm proceeds to step S**115** where the haptic force is set to zero, step S**117** where collisionDetectedFlag(t) is set to

zero, and step S119 where the time advances to t=t+1. If step S105 determines that the HIP(t) is inside a voxel bounding box, the algorithm proceeds to step S107 and searches candidate polygons along a line segment of HIP(t) from a voxel lookup table. In step S109, the algorithm retrieves polygonal information from a polygon lookup table. In step S111, the algorithm tests an intersection of the line segment of HIP(t) with the polygons and, in step S113, determines whether an initial collision is detected. If no collision is detected, the algorithm proceeds to steps S115, S117, and S119 as described above. If a collision is detected, the algorithm proceeds to step S132 (described below).

[0165] In contrast, in step S101, if collisionDetected-Flag(t−1) has a value of 1, the algorithm follows the right branch of the flowchart. In step S102, the algorithm maps HIP(t) into voxel coordinates. In step S104, the algorithm searches neighboring polygons at the HIP(t) from a voxel lookup table. In step S106, the algorithm retrieves polygonal information from a polygon lookup table. In step S108, each neighboring polygon is tested to determine whether it is intersected by the line segment from HIP(t−1) to HIP(t). In step S110, the algorithm uses this information to determine whether the HIP(t) has exited the polygons. If so, the HIP is no longer penetrating the haptic object, and the algorithm proceeds to steps S115, S117, and S119 as described above. If step S110 determines that the HIP has not exited the polygons, the algorithm proceeds to step S112 where the algorithm projects the HIP(t) on each neighboring polygon along the corresponding surface normal vectors of the polygons. If the projected HIP(t) is within a polygon, the algorithm sets the polygon as an On-Polygon and stores the intersecting point. Otherwise, the algorithm finds a point on a boundary of the polygon that is closest to the projected HIP(t) (all within the plane of the polygon) and stores the point. This process is repeated for each neighboring polygon. The algorithm then has decision points based on whether an Active Polygon from the previous time cycle, AP(t−1), was set to be an On-Polygon in step 22 and whether only a single polygon was set to be an On-Polygon in the current cycle. Each case is handled as described below.

[0166] In step S114, the algorithm determines whether a previous active polygon (on which the virtual proxy point was in contact) is still an On-Polygon. If so, in step S124 (ActivePolygonPriority), this polygonal surface has priority to be the active polygon, even if other polygons are identified as On-Polygons. AP(t) is therefore maintained, and VP(t) is set at the closest point on the active polygonal surface. For example, FIG. 51 A shows a convex portion of a virtual object defined by two adjoining surfaces 540 and 542. When the HIP at t−1 was at a location 544, the surface 540 is On-Polygon and 542 is not On-Polygon. The virtual proxy point location at t−1 lies at a location 548. If the HIP moves to a location 546, both of the surfaces 540 and 542 are On-Polygons and locations 550 and 552 are candidates for proxy point location. In this situation, the surface 540 will be selected as an active polygon and the proxy point location will be updated at the location 550. Granting the previous active polygon priority in this way prevents the choice of the location 552 for the proxy point, which would result in an unnatural jump in the proxy point position and the resulting haptic interaction forces experienced by the user.

[0167] If step S114 determines that the previous active polygon is not an On-Polygon, the algorithm proceeds to step S116 to determine whether a single On-Polygon is detected. If a single On-Polygon is not detected in step S116, the algorithm checks again in step S120. If a single On-Polygon is detected in step S116, the algorithm proceeds to step S118 and augments the On-Polygons for a concave corner before checking again for a single On-Polygon in step S120. If a single On-Polygon is detected in step S120, the algorithm proceeds to step S126 (described below). If a single On-Polygon is not detected in step S120, the algorithm proceeds to step S122 and determines whether multiple On-Polygons are detected. If so, the algorithm proceeds to step S128 (described below). Otherwise, the algorithm proceeds to step S130 (described below).

[0168] In step S126 (OnPolygonPriority), AP(t) is updated with a new On-Polygon and VP(t) is set at the closest point on the active polygonal surface. For example, as shown in FIG. 51B, a virtual object has two adjoining surfaces 554 and 556. At a time t−1, the HIP is at a location 558 and the proxy point is at a location 562. When the HIP crosses over a surface border line 564 as the HIP moves from the location 558 to a location 560, a surface 556 becomes On-Polygon and a location 566 becomes the new proxy point location. Thus, if a new single On-Polygon is detected, then the new single On-Polygon becomes the active polygon.

[0169] In step S128 (ContinuousSurfacePriority), AP(t) is selected based on force vector deviation criteria and VP(t) is set at the closest point on the active polygonal surface. The algorithm detects the multiple new On-Polygons as illustrated in FIG. 51C, which shows a convex portion of a virtual object defined by three surfaces, 568, 570, and 572. As the HIP moves from a location 574 to a location 578, the algorithm detects two new On-Polygon surfaces, 570 and 572. Thus, locations 580 and 582 are candidates for a new virtual proxy point location. In this situation, the algorithm computes possible candidates of force vector, excluding a damping component, and compares a force vector deviation from a previous force vector deviation. The algorithm determines the active polygon so as to minimize the following objective function:

$$J_{continuousSurfcae} = \min_i \| f_{si,t} \cdot f_{t-1} \|$$

where $f_{si,t}$ represents a spring force vector defined by a current location of the HIP and a possible location of the virtual proxy point on the ith polygon and f_{t-1} represents a haptic force displayed at previous time. In one embodiment, the surface 570 will be the new active polygon and a location 580 will be the new proxy point position.

[0170] In step S130 (MinimumForcePriority), AP(t) is based on minimum force criteria and VP(t) is set at the closest point on the active polygonal surface. As shown in FIG. 5 ID, the HIP lies at position where no On-Polygon can be detected. FIG. 51D, illustrates a concave portion of a virtual object defined by three surfaces, 584, 586, and 588. When the HIP moves from a location 590 to a location 594, no surface is On-Polygon. A location 596 is the closest point to the surfaces 586 and 584, a location 598 is the closest point to the surface 588. In this situation, the algorithm computes distances between the current HIP and possible proxy point locations and determines a virtual proxy location to minimize the following objective function:

$$J_{minimumSpringForce} = \min_i \|x_{hip} - x_{i,vp}\|$$

where $x_{i,vp}$ represents a position of the possible virtual proxy point on the ith polygon and x_{hip} represents a position of the current haptic interface point. In this situation, the algorithm sets either the surface **584** or the surface **586** as the On-Polygon depending on their processing sequence and the location **596** will be the proxy point location.

[**0171**] In step S**132** (ContactPolygonPriority), AP(t) is updated with an intersected polygon and VP(t) is set at the closest point on the active polygonal surface. The algorithm augments the On-Polygon objects when a haptic interface point lies in a concave corner where the algorithm detects one On-Polygonal object and multiple concave surfaces. In this situation, the application sets the concave polygonal surface to On-Polygon so that continuous haptic rendering can happen at the concave corner. **FIGS. 52A and 52B** show a portion of a concave corner represented by three surfaces, **500**, **502**, and **504**. As the haptic interface point moves from a location **506** (with a proxy point location **508**) to a location **510**, the surface **504** becomes the only On-Polygonal object. In order to avoid the situation in which the algorithm sets the surface **504** as an active polygonal surface due to On-Polygon priority behavior and selects a location **514** as the proxy point location, the algorithm augments the two concave surfaces **500** and **502** into On-Polygon objects. As a result, a location **512** will be a proxy point location according to continuous surface priority behavior.

[**0172**] In step S**134**, stiffness and damping matrices defined in tool coordinates as constant parameters are transformed into an inertial coordinate frame. When the physical haptic device **30** has different transmission devices, such as a cable driven transmission and a direct-driven transmission, isotropic spatial stiffness and damping gains can cause instability because the physical system has different dynamic properties in different directions. For this reason, the spatial stiffness and damping matrices can be defined with respect to the tool coordinates and need to be transformed into the inertial coordinate frame. The algorithm computes an adjoint transformation matrix based on current rotational and translational matrices and transforms the spatial stiffness and damping matrices. Let ${}^{T}K_s$ and ${}^{I}K_s$ denote the stiffness matrices measured in tool frame and inertial frame, respectively. Let Ad_g denote the adjoint transformation matrix given as

$$Ad_g = \begin{bmatrix} R & \hat{p}R \\ 0 & R \end{bmatrix}$$

[**0173**] Given a vector $p=(px, py, pz)^T$, $\hat{p}$ denotes a skew-symmetric matrix used for representing a cross product as a matrix-vector product:

$$\hat{p} = \begin{pmatrix} 0 & -p_x & p_y \\ p_x & 0 & -p_z \\ -p_y & p_z & 0 \end{pmatrix}$$

where R is the rotational matrix and p is the translational vector.

[**0174**] The algorithm computes the stiffness matrix in the inertial frame:

$${}^{I}K_S = Ad_g^{T\,T} K_S Ad_g$$

[**0175**] In step S**136**, the algorithm computes a spring haptic force vector based on the location of the haptic interface point and the virtual proxy point location according to Hooke's law:

$$F_{sping}(t) = {}^{I}K_S(x_{vp} - x_{hip})$$

where x_{vp} represents a position of a current virtual proxy point, and x_{hip} represents a position of a current haptic interface point.

[**0176**] In step S**138**, the algorithm computes a damping haptic force vector based on the relative motion between the haptic interface point and the virtual proxy point:

$$F_{damping}(t) = {}^{I}K_D(\dot{x}_{vp} - \dot{x}_{hip})$$

where $\dot{x}_{vp}$ represents motion of the virtual proxy point, $\dot{x}_{hip}$ represents motion of the haptic interface point, and ${}^{I}K_D$ represents the spatial damping matrix in an inertial frame.

[**0177**] In step S**140**, the sum of the damping force and spring force is sent to the physical haptic device **30** as a desired force output (step S**718** of **FIG. 43**). Prior to controlling the actuators (block **2512** of **FIG. 40**) of the haptic device **30** to output force feedback, the force mapping process (block **2510** of **FIG. 40**) converts the desired force, $F_{desired}$, to joint torque, τ:

$$\tau = J^T F_{desired}$$

where j^T is a Jacobian transpose. The computing system **20** then controls the actuators of the haptic device **30** to output the joint torque, τ.

[**0178**] In step S**142**, collisionDetectedFlag(t)=1. In step S**144**, the time advances to t=t+1. In cases where there may be a transmission with compliance, backlash, hysteresis, or nonlinearities between the haptic device drive (e.g., motors) and position outputs (e.g., joints), it is beneficial to include position sensors on both the drive end and load end of the transmission. The load end sensors are used to compute all joint and endpoint positions because they will most accurately reflect the actual values. The drive end sensors are used to compute velocities in any damping computations, such as for $F_{damping}$ above, which helps avoid exciting the transmission dynamics.

[**0179**] According to one embodiment, the desired force feedback (or output wrench) of the haptic device **30** is determined based on a proximity of a portion of the haptic device **30** (e.g., the tool **50**) to a virtual (or haptic) boundary associated with the representation of the anatomy. Thus, if

the tool **50** is disposed a sufficient distance from the haptic boundary, a controller commands no haptic forces, and the user is free to move the tool **50** as if exploring empty space. However, as the tool **50** approaches or contacts the haptic boundary, the controller commands torques to the motors so as to exert the appropriate wrench on the user's hand via the interface **37**. Preferably, a magnitude of the force feedback increases as the tool **50** approaches the virtual boundary and does not present a discontinuous step that may induce oscillation or unwanted vibration. For example, as the tool **50** approaches the haptic boundary, the haptic device **30** may exert a force in a direction opposite a direction of movement of the user interface **37** such that the user perceives a repulsive or counteracting force that slows and/or stops movement of the tool **50**. In one embodiment, a rate of increase of the force as the tool **50** continues moving toward the haptic boundary may be, for example, in a range of 5 N/mm to 50 N/mm. In another embodiment, the rate of increase of the force may be approximately 20 N/mm. In this manner, the user is constrained to not penetrate the haptic boundary too deeply. When the tool **50** contacts the haptic boundary, the force may be such that the user feels as if the tool **50** has collided with a physical object, such as a wall. The magnitude of the force may prevent the user from penetrating the haptic boundary (e.g., a magnitude of approximately 100 N or greater) but is preferably set so that the user may breach the haptic boundary if desired (e.g., a magnitude in a range of approximately 20 N to approximately 60 N). Thus, the computing system **20** may be programmed to permit the user to overcome the force feedback and move the haptic device **30** to a desired location. In this manner, the haptic device **30** constrains the user against inadvertently violating the haptic boundary, but the user has the option to overpower the haptic device **30** and thus retains full control over the surgical procedure.

[**0180**] In one embodiment, the surgical system **10** includes a haptic tuning feature for customizing a force feedback function of the haptic object for a particular user. Such a feature is advantageous because each user has a unique surgical technique. Thus, different users may use differing amounts of force when maneuvering the tool **50**. For example, users who maneuver the tool **50** with a light touch may sense haptic feedback earlier than users with a heavier touch. Rather than requiring the user with the heavier touch to alter his surgical technique to sufficiently sense the haptic feedback, the haptic tuning feature enables the force feedback function to be adjusted to accommodate each particular user. By adjusting (or tuning) the force feedback function, the user can manipulate the tool **50** with his preferred degree of force and still sufficiently perceive the haptic feedback exerted by the haptic device **30**. As a result, the user's ability to maintain the tool within the haptic boundary is improved. For example, as shown in **FIG. 11A**, a force feedback curve includes a function F(d) that relates force F to distance d. The function F(d), for example, may result from or be a product of the haptic object, a coupling stiffness, or a stiffness function. In one embodiment, F_i is a typical haptic interaction force for a user (or a group of users), and d_i is a penetration depth or distance (e.g., penetration of the tool **50** into the haptic object) where $F_i=F(d_i)$ is true. As shown in **FIG. 11B**, shifting or offsetting the function F(d) to the left by, for example, d_i, results in a force feedback function $F(d+d_i)$ that causes the force F to be applied earlier (i.e., beginning at a penetration distance of $-d_i$ rather than at a penetration distance of zero) in a tool's approach to a haptic boundary. Similarly, shifting or offsetting the function F(d) to the right causes the force F to be applied later in the tool's approach to the haptic boundary. Thus, for a user with a surgical technique that is forceful, it is advantageous to offset the function F(d) to the left to prevent the user from inadvertently pushing too far into the haptic boundary. Thus, haptic tuning may be accomplished by offsetting a force feedback curve for controlling the haptic device **30** by a desired value. Haptic tuning can also be accomplished by altering a size of a haptic object. For example, a size of a repulsive haptic object **120***a* (shown in **FIG. 11C**) can be increased resulting in a haptic object **120***b* (shown in **FIG. 11D**). Similarly, a size of a representation of a surgical tool coupled to the haptic device **30** may be altered. For example, a size of a radius of a tip of a virtual tool **124***a* (shown in **FIG. 11E**) that interacts with a haptic object **122** can be increased resulting in a virtual tool **124***b* (shown in **FIG. 11F**). For a haptic object that acts as a container, tuning can be accomplished, for example, by reducing a size of the haptic object.

[**0181**] To enable each user to tune the force feedback function, the computing system **20** preferably includes programming to enable a graphical selection interface that can be displayed on the display device **23**. For example, as shown in **FIGS. 11G and 11H**, respectively, the graphical selection interface may be a graphical interface **217***a* that enables the user to set a tuning value, for example, between 0.0 and 1.0 and/or a graphical interface **217***b* that enables the user to select, for example, tuning for a "Light,""Medium," or "Heavy" touch. The computing system **20** may also be programmed to store a desired value of a tuning setting and to associate the desired value with a particular user (e.g., using a user ID tied to a user preference data file) so that the user does not have to select the tuning setting prior to each use of the surgical system **10**.

[**0182**] The haptic device **30** is preferably configured to operate in various operating modes. For example, the haptic device **30** may be programmed to operate in an input mode, a hold mode, a safety mode, a free mode, an approach mode, a haptic (or burring) mode, and/or any other suitable mode. The operating mode may be selected manually by the user (e.g., using a selection button represented graphically on the display device **23** or a mode switch located on the haptic device **30** and/or the computing system **20**) and/or automatically by a controller or software process. In the input mode, the haptic device **30** is enabled for use as an input device to input information to the surgical system **10**. When the haptic device **30** is in the input mode, the user may operate the haptic device **30** as a joystick or other input device, for example, as described above in connection with the end effector **35** and/or in U.S. patent application Ser. No. 10/384,078 (Pub. No. US 2004/0034282), which is hereby incorporated by reference herein in its entirety. Other methods of inputting information to the surgical system **10** include, for example, moving the wrist **36**, moving a joint of the arm **33**, and/or moving the arm **33** (or a portion thereof). For example, moving the arm **33** toward an object (e.g., a tracked object) may comprise a first input. Similarly, moving the arm **33** toward the object and twisting the wrist **36** may comprise a second input. Thus, the surgical system **10** may identify or distinguish user input based on, for example, a pose of the haptic device **30** with respect to a tracked object, movement of a portion of the haptic device **30** (e.g., the wrist

36), or a combination of pose and movement. In the hold mode, the arm **33** of the haptic device **30** may be locked in a particular pose. For example, the arm **33** may be locked using brakes, control servoing techniques, and/or any other appropriate hardware and/or software for stabilizing the arm **33**. The user may desire to place the haptic device **30** in the hold mode, for example, during an activity such as bone cutting to rest, confer with a colleague, allow cleaning and irrigation of the surgical site, and the like. In the safety mode, the tool **50** coupled to the haptic device **30** may be disabled, for example, by shutting off power to the tool **50**. In one embodiment, the safety mode and the hold mode may be executed simultaneously so that the tool **50** is disabled when the arm **33** of the haptic device **30** is locked in position.

[**0183**] In the free mode, the end effector **35** of the haptic device **30** is freely moveable within the workspace of the haptic device **30**. Power to the tool **50** is preferably deactivated, and the haptic device **30** may be adapted to feel weightless to the user. A weightless feeling may be achieved, for example, by computing gravitational loads acting on the segments **33***a*, **33***b*, and **33***c* of the arm **33** and controlling motors of the haptic device **30** to counteract the gravitational loads. As a result, the user does not have to support the weight of the arm. The haptic device **30** may be in the free mode, for example, until the user is ready to direct the tool **50** to a surgical site on the patient's anatomy.

[**0184**] In the approach mode, the haptic device **30** is configured to guide the tool **50** to a target object, such as, for example, a surgical site, feature of interest on the patient's anatomy, and/or haptic object registered to the patient, while avoiding critical structures and anatomy. For example, in one embodiment, the approach mode enables interactive haptic positioning of the tool **50** as described in U.S. patent application Ser. No. 10/384,194 (Pub. No. US 2004/0034283), which is hereby incorporated by reference herein in its entirety. In another embodiment, the haptic rendering application may include a haptic object defining an approach volume (or boundary) that constrains the tool **50** to move toward the target object while avoiding sensitive features such as blood vessels, tendons, nerves, soft tissues, bone, existing implants, and the like. For example, as shown in **FIG. 1**, the approach volume may include the haptic object **300**, which is substantially cone-shaped, funneling from a large diameter to a small diameter in a direction toward the target object (e.g., a proximal end of the tibia T or a distal end of the femur F). In operation, the user may freely move the tool **50** within the boundaries of the approach volume. As the user moves the tool **50** through the approach volume, however, the tapering funnel shape constrains tool movement so that the tool **50** does not penetrate the boundaries of the approach volume. In this manner, the tool **50** is guided directly to the surgical site. In another embodiment, shown in **FIG. 9**, the haptic rendering application creates a virtual object that represents a pathway from a first position to a second position. For example, the virtual object may include the haptic object **310**, which is a virtual guide wire (e.g., a line) defining a pathway from a first position (e.g., a position of the tool **50** in physical space) to a second position that includes a target region of the anatomy (e.g., a target object such as the haptic object **206**). In the approach mode, the virtual object is activated so that movement of a portion of the haptic device **30** (e.g., the tool **50**) is constrained along the pathway defined by the haptic object **310**. The surgical system **10** deactivates the virtual object when the tool **50** reaches the second position and activates the target object (e.g., the haptic object **206**). The tool **50** may be automatically placed in the haptic (or burring) mode when the haptic object **206** is activated. In a preferred embodiment, the virtual object may be deactivated to enable the tool **50** to deviate from the pathway. Thus, the user can override the haptic guidance associated with the haptic object **310** to deviate from the guide wire path and maneuver the tool **50** around untracked objects (e.g., retractors, lamps, etc.) the cannot be accounted for when the virtual guide wire is created. Thus, the approach mode enables the user to quickly deliver the tool **50** to a target object while avoiding critical structures and anatomy. In the approach mode, power to the tool **50** is preferably deactivated so that the tool is not accidentally energized, for example, when the user is inserting the tool through an incision or navigating soft tissue in a joint. The approach mode generally precedes the haptic mode.

[**0185**] In the haptic (or burring) mode, the haptic device **30** is configured to provide haptic guidance to the user during a surgical activity such as bone preparation. In one embodiment, as shown in **FIG. 9**, the haptic rendering application may include the haptic object **206** defining a cutting volume on the tibia T. The haptic object **206** may have a shape that substantially corresponds to a shape of a surface **74***a* of the tibial component **74** (shown in **FIG. 10B**). Alternatively, the haptic object **206** may have a shape that is slightly larger than the shape of the surface **74***a* of the tibial component **74**. One advantage of making the haptic object **206** larger than the implant is that the cutting volume defined by the haptic object **206** is then large enough to accommodate both the implant and a cement mantle that is disposed between the implant and the bone to secure the implant to the bone. A haptic object having a size that deviates from the size of the implant also enables implementation of the haptic tuning feature described above in connection with **FIGS. 11A** to **11**F. The haptic device **30** may enter the haptic mode automatically, for example, when the tip of the tool **50** approaches a predefined point related to a feature of interest. In the haptic mode, the haptic object **206** may also be dynamically modified (e.g., by enabling and disabling portions of a haptic surface) to improve performance of the haptic device **30** when sculpting complex shapes or shapes with high curvature as described, for example, in U.S. patent application Ser. No. 10/384,194 (Pub. No. US 2004/0034283), which is hereby incorporated by reference herein in its entirety. In the haptic mode, power to the tool **50** is activated, and the tip of the tool **50** is constrained to stay within the cutting volume to enable a precise bone resection.

[**0186**] The haptic device **30** may utilize any suitable haptic control scheme, such as, for example, admittance control, impedance control, or hybrid control. In an admittance control mode, the haptic device **30** accepts force input and yields position (or motion) output. For example, the haptic device **30** measures or senses a wrench at a particular location on the haptic device **30** (e.g., the user interface **37**) and acts to modify a position of the haptic device **30**. In an impedance control mode, the haptic device **30** accepts position (or motion) input and yields wrench output. For example, the haptic device **30** measures, senses, and/or calculates a position (i.e., position, orientation, velocity, and/or acceleration) of the tool **50** and applies an appropriate corresponding wrench. In a hybrid control mode, the haptic

device **30** utilizes both admittance and impedance control. For example, a workspace of the haptic device **30** may be divided into a first subspace in which admittance control is used and a second subspace in which impedance control is used. In a preferred embodiment, the haptic device **30** operates in the impedance control mode.

[**0187**] During a surgical procedure, the computing system **20** guides the user through the procedure. For example, the computing system **20** may be programmed to generate a display configured to guide the user manipulating the haptic device **30** through the procedure. The display may comprise screens shown on the display device **23** that include, for example, predefined pages and/or images corresponding to specific steps of the procedure. The display may also prompt the user to perform one or more tasks. For example, the display may instruct a user to select anatomical landmarks on a representation of the anatomy (discussed below in connection with steps S**3** and S**4** of **FIG. 13**). In one embodiment, as shown in **FIG. 12**, the screen may include a navigation pane **600** for displaying images related to a current step of the procedure; a tracked object pane **602** for showing tracked objects in relation to one another; an information pane **604** for displaying information related to the current step of the procedure, such as, for example, measurement data, error data, status information, selection buttons, and the like; and a pane **606** for advancing to subsequent steps in the procedure and/or returning to previous steps.

[**0188**] Displays or screens associated with the surgical procedure may be configured to communicate visual information to the user regarding the procedure. For example, as shown in **FIG. 12**, the navigation pane **600** may create and display a representation of the anatomy (such as an image or representation of a bone) and a representation **616** of the surgical tool **50**. For a bone preparation process, the surgical system **10** may facilitate the step of preparing the bone to receive an implant by creating a representation **612** of a portion of material to be removed from the bone, superimposing the representation **612** of the portion of material to be removed on the representation of the bone, and updating the representation **612** of the portion of material to be removed with a representation **614** of a portion of material actually removed by the tool **50** as the user manipulates the haptic device **30**. To further aid the user, the surgical system **10** can update the representation of the bone and the representation **616** of the tool **50** as the bone and the tool **50** move. In one embodiment, the representation **612** of the portion of material to be removed corresponds to a portion of a virtual object associated with (or registered to) the bone. Thus, the virtual object represents the portion of material to be removed from the anatomy. For example, the virtual object may have a shape substantially corresponding to a shape of a surface of an implant to be fitted to the anatomy (e.g., in a cementless implant application). For cemented implant applications, the virtual object may have a shape that is larger than a shape of the implant to allow room for a cement mantle between the implant and the bone. The above-described bone preparation steps may be performed, for example, on a first bone (e.g., the tibia T) and then repeated for a second bone (e.g., the femur F).

[**0189**] In one embodiment, the portion of bone to be removed may be indicated for example, using a color that is different from a color of surrounding bone. For example, the portion of bone to be removed may be colored green while the surrounding bone is colored white. As the user removes bone with the tool **50**, the computing system **20** updates the image in the navigation pane **600** so that when the tool **50** reaches a desired cutting depth, the color changes from green to white. Similarly, if the tool **50** cuts beyond the desired cutting depth, the color changes from white to red. Thus, the surgical system **10** creates a representation of a portion of material to be removed in a first color and, when a desired amount of material has been removed, creates a representation of the material removed by the haptic device **30** in a second color. If the material removed by the haptic device exceeds the desired amount of material, the surgical system **10** creates a representation of the material removed in a third color. In a preferred embodiment, a haptic object includes an array of volume elements (i.e., voxels) having a first portion corresponding to a portion of bone to be removed, a second portion corresponding to surrounding bone, and a third portion corresponding to a cutting depth that is outside a predefined cutting volume. The voxels in the first portion may be a first color (e.g., green), the voxels in the second portion may be a second color (e.g., white), and the voxels in the third portion may be a third color (e.g., red). As the tool **50** overlaps a voxel, the voxel is cleared thereby exposing an adjacent underlying voxel. Thus, if the user cuts too deeply with the tool **50**, green and/or white voxels may be cleared to expose underlying red voxels. In another embodiment, the surgical system **10** may provide a visual indication of a distance between the tip of the tool **50** and a surface of a haptic object in registration with the patient as described, for example, in U.S. patent application Ser. No. 10/621,119 (Pub. No. 2004/0106916), which is hereby incorporated by reference herein in its entirety. The navigation pane **600** may also include, for example, a representation of a current position of the tool **50**, a desired trajectory of the tool **50**, a representation of an implant, and/the like.

[**0190**] In addition to communicating with the user visually, the computing system **20** may be programmed to emit audible signals (e.g., via the acoustic device). For example, in one embodiment, the computing system **20** may emit sounds (e.g., beeps) indicating that a cutting depth of the tool **50** is too shallow, approximately correct, or too deep. In another embodiment, the surgical system **10** may provide an audible indication of a distance between the tip of the tool **50** and a surface of a haptic object in registration with the patient as described, for example, in U.S. patent application Ser. No. 10/621,119 (Pub. No. US 2004/0106916), which is hereby incorporated by reference herein in its entirety. The computing system **20** may also be programmed to control the haptic device **30** to provide tactile feedback to the user, such as, for example, a vibration indicating that the tool **50** has reached or exceeded the desired cutting depth. The software of the computing system **20** may also include programs or processes that automatically prompt a user to perform certain tasks, such as, for example, segmenting an image of a diagnostic image data set, selecting points on the patient's anatomy to define a mechanical axis, touching (or "painting") points on a surface of the bone with a registration probe, entering data (e.g., implant size, burr size, etc.), and the like.

[**0191**] **FIG. 13** illustrates an embodiment of a process for using the surgical system **10** for surgical planning and navigation of a unicondylar knee replacement. The process of **FIG. 13** is intended as an exemplary illustration only. In

other embodiments, the order of the steps of the process may be rearranged in any manner suitable for a particular surgical application. Additionally, other embodiments may include all, some, or only portions of the steps illustrated in **FIG. 13** and may combine any of the steps of **FIG. 13** with existing and/or later developed surgical approaches. The unicondylar knee replacement procedure detailed in the process of **FIG. 13** is for a medial side of the knee. The same process may be used, however, for a lateral side of the knee. Moreover, the illustrated unicondylar procedure is exemplary only. The surgical system **10** may also be used to perform a total knee replacement procedure or other joint replacement procedure involving installation of an implant. The implant may include any implant or prosthetic device, such as, for example, a total knee implant; a unicondylar knee implant; a modular knee implant; implants for other joints including hip, shoulder, elbow, wrist, ankle, and spine; and/or any other orthopedic and/or musculoskeletal implant, including implants of conventional materials and more exotic implants, such as orthobiologics, drug delivery implants, and cell delivery implants. In one embodiment, the implant is a modular knee implant as described in U.S. patent application Ser. No. 11/312,741, filed Dec. 30, 2005, which is hereby incorporated by reference herein in its entirety.

[**0192**] In the embodiment of **FIG. 13**, steps S**1** to S**4** are performed preoperatively, and steps S**5** to S**14** are performed intraoperatively. In step S**1**, patient information or data may be input to the surgical system **10**. In step S**2**, a preoperative diagnostic image (e.g., a CT data file) is loaded into the surgical system **10** and segmented. In step S**3**, femoral landmarks are selected. In step S**4**, tibial landmarks are selected. In step S**5**, a homing process is performed on the haptic device **30** to initialize position sensors in the arm **33** of the haptic device **30**. In step S**6**, calibration of a registration probe is verified. In step S**7**, the anatomy trackers **43***a* and **43***b* are attached to the patient. In step S**8**, patient anatomy is registered. In step S**9**, the haptic device **30** is calibrated. In step S**10**, an initial placement of a tibial implant (e.g., a tibial component **74** as shown in **FIG. 16B**) is planned. A depth of the initial placement may be guided by points that are selected on a surface of the tibial plateau cartilage and transferred to a planning screen on the display device **23** using the registration computed in step S**8**. In step S**11**, the tibia T is prepared or sculpted. In step S**12**, a tibial trial implant is fitted to the prepared surface of the tibia T. In step S**13**, an initial placement of a femoral implant (e.g., a femoral component **72** as shown in **FIG. 16A**) is planned, for example, using points related to a position of the tibial trial implant at various flexions of the leg. In step S**14**, the femur F is prepared or sculpted. In step S**15**, a femoral trail implant is fitted to the prepared surface of the femur F. A trial reduction process is performed in which the user assesses the fit of the femoral and tibial trial implants and makes any desired adjustments (e.g., repeating implant planning and/or bone sculpting) prior to installing the femoral component **72** and the tibial component **74**.

[**0193**] In step S**1**, patient information may be input to the surgical system **10**. For example, the surgical system **10** may display a screen on the display device **23** requesting information about the patient. Patient information may include any relevant patient data, such as, for example, name, birth date, identification number, sex, height, and weight. Patient information may also include information related to the procedure to be performed, such as, for example, specifying the appropriate leg (e.g., left or right), specifying the portion of the joint to be replaced (medial, lateral, total), and selecting preoperative diagnostic image data files (e.g., CT data files) of the patient's anatomy. Patient information may be input to the surgical system **10** in any known manner. For example, the user may directly enter the patient information or the patient information may be downloaded into the surgical system **10** from a hospital network or electronic storage medium. Preferably, patient information is recorded when the patient's anatomy is imaged, is saved in an image data file (e.g., a CT data file), and is loaded into the surgical system **10** along with the image data file in step S**2** below. The computing system **20** may also request information related to the user (e.g., name, identification number, PIN number, etc.), the surgical facility, and/or any other information useful for identification, security, or record keeping purposes. As with the patient data, user information may also be included in the image data file. As a safeguard, the computing system **20** may include a verification feature that prompts the surgeon (or other licensed medical professional) to verify patient information that has been input to the surgical system **10**.

[**0194**] In step S**2**, a representation of the anatomy is created by loading image data files containing preoperative diagnostic images (e.g., an upper leg image, a knee image, and a lower leg image) into the surgical system **10**. The diagnostic images constitute a representation of the anatomy. Additional representations of the anatomy may be generated by segmenting the images. For example, the surgical system **10** may display a screen **81***a* (shown in **FIG. 15**) to guide the user through the segmentation process for the femur F and a screen **81***b* (shown in **FIG. 16**) to guide the user through the segmentation process for the tibia T. As shown in **FIGS. 15 and 16**, the preoperative diagnostic images are divided into segments or slices that span the anatomy of interest. The segmentation data is used by the surgical system **10** to create a representation of the anatomy of the patient, including, for example, a representation of a first bone and a representation of a second bone. The first and second bones may be the femur F and the tibia T (or vice versa). In one embodiment, three-dimensional computer models representative of the anatomy are created based on object boundaries (e.g., at bone or cartilage surfaces) generated by the segmentation. The greater the number of segments or slices, the higher the accuracy of the model. In one embodiment, the number of slices taken across a portion of the anatomy of interest is 30 slices. In another embodiment, the number of slices taken may be in a range of 20 slices to 100 slices. The segmentation process may utilize any suitable segmentation method, such as for example, texture-based segmentation, thresholding-based interactive segmentation, region-based object segmentation, and/or polygon-based manual tracing. In one embodiment, an "edge measure" based interactive segmentation known as "livewire" is used.

[**0195**] In steps S**3** and S**4**, the user designates landmarks on the representation of the first bone and the representation of the second bone. For example, in step S**3**, the user may designate femoral landmarks on an image of the femur F. The femoral landmarks are used by the surgical system **10** to associate (or register) the patient's physical anatomy with the representation of the anatomy (e.g., diagnostic images, models generated from segmentation, anatomical models, etc.). As shown in FIGS. **17** to **19**, the surgical system **10**

generates screens **82***a*, **82***b*, and **82***c*, respectively, to guide the user in specifying the femoral landmarks. For example, the surgical system **10** may direct the user to specify a hip center (**FIG. 17**), a medial epicondyle (**FIG. 18**), and a lateral epicondyle (**FIG. 19**). In one embodiment, the user may select the femoral landmarks on a displayed image using a mouse or touch screen. In another embodiment, the computer may be programmed to determine the location of the femoral landmarks in the images, for example, using algorithms designed to locate distinguishing features in the diagnostic images.

[**0196**] Similarly, in step S**4**, the user may designate tibial landmarks on an image of the tibia T. The tibial landmarks are used by the surgical system **10** to associate (or register) the patient's physical anatomy with the representation of the anatomy (e.g., diagnostic images, models generated from segmentation, anatomical models, etc.). As shown in FIGS. **20** to **23**, the surgical system **10** generates screens **83***a*, **83***b*, **83***c*, and **83***d*, respectively, to guide the user in specifying the tibial landmarks. For example, the surgical system **10** may direct the user to specify a medial malleolus (**FIG. 20**), a lateral malleolus (**FIG. 21**), a rotational landmark (**FIG. 22**), and a knee center (**FIG. 23**). As shown in **FIG. 22**, the rotational landmark may be, for example, intersecting axes **183** that the user adjusts to be parallel to the anterior and posterior portions of the transverse view of the anatomy in the screen **83***c*. The rotational landmark enables the surgical system **10** to account for any rotation of the leg L in the diagnostic image (e.g., if the CT scan was taken with the leg L leaning to the side rather than in exact anterior-posterior alignment) and to adjust the transverse view so that the anterior and posterior portions are aligned (e.g., as shown in a frame **806** of **FIG. 35**). In one embodiment, the user may select the tibial landmarks on a displayed image using a mouse or touch screen. In another embodiment, the computer may be programmed to determine the tibial landmarks, for example, using algorithms designed to locate distinguishing features in the diagnostic images.

[**0197**] In step S**5**, a homing process initializes the position sensors (e.g., encoders) of the haptic device **30** to determine an initial pose of the arm **33**. Homing may be accomplished, for example, by manipulating the arm **33** so that each joint encoder is rotated until an index marker on the encoder is read. The index marker is an absolute reference on the encoder that correlates to a known absolute position of a joint. Thus, once the index marker is read, the control system of the haptic device **30** knows that the joint is in an absolute position. As the arm **33** continues to move, subsequent positions of the joint can be calculated based on the absolute position and subsequent displacement of the encoder. The surgical system **10** may guide the user through the homing process by providing instructions regarding the positions in which the user should place the arm **33**. The instructions may include, for example, images displayed on the display device **23** showing the positions into which the arm **33** should be moved.

[**0198**] In step S**6**, an instrument (e.g., a registration probe such as the instrument **150**) is checked to verify that the instrument is calibrated. For example, step S**6** may be used to verify that a registration probe has a proper physical configuration. As discussed above in connection with the instrument tracker **49**, calibration of a probe that includes the instrument tracker **49** may be accomplished by inserting a tip of the probe into the divot **47***a* of the end effector tracker **47**, holding the tip in place, and detecting the instrument tracker **49** and the end effector tracker **47** with the detection device **41**. The detection device **41** acquires pose data, and the surgical system **10** compares an actual geometric relationship between the trackers **49** and **47** to an expected geometric relationship between the trackers **49** and **47**. Deviation between the actual and expected geometric relationships indicates one or more physical parameters of the probe is out of calibration. As shown in **FIG. 24**, during the verification process, the surgical system **10** may display a screen **84** showing a graphical representation of the probe, the instrument tracker **49**, and the end effector tracker **47** on the display device **23**.

[**0199**] Prior to step S**7**, the patient arrives in the operating room. As shown in **FIG. 1**, the patient (only a leg L is shown) is positioned on an operating table **102**, and the haptic device **30** is positioned relative to the patient so that the haptic device **30** can attain a variety of poses useful for the procedure. To achieve an appropriate level of sterility, the haptic device **30** may be sterilized in any suitable manner. For example, the end effector **35** and the tool **50** may be sterilized using conventional sterilization processes, and other portions of the haptic device **30** may be sterilized and/or covered with a sterile covering or drape. In one embodiment, the arm **33** and the base **32** of the haptic device **30** are covered with a sterile plastic wrapping, and the platform **39** is covered with a sterile drape.

[**0200**] To elevate the leg L of the patient and enable the leg L to be bent at different angles, the leg L may be supported or braced in a leg holder (or support device) that can be moved into various positions. In one embodiment, the leg holder is a manually adjustable leg holder **62**. As shown in **FIG. 14A**, the leg holder **62** includes a first portion **62***a* and a second portion **62***b* slidably disposed on a base **64** and connected at a hinge **62***c*. The base **64** includes a locking mechanism (not shown) for fixing the first and second portions **62***a* and **62***b* in position. The leg L may be secured on the leg holder **62** in any suitable manner, such as, for example, using one or more straps **63**. Alternatively or in addition to tracking a pose of the bones of the leg L (e.g., with the anatomy trackers **43***a* and **43***b* or the mechanical tracking system **240**), a pose of the leg holder **62** may be tracked (e.g., with position sensors, a non-mechanical tracking system, or a mechanical tracking system as described above). If only the leg holder **62** is tracked, the leg L should be sufficiently secured to the leg holder **62** (e.g., with the straps **63**) so as to prevent relative motion between the leg L and the leg holder **62**. In operation, to move the leg L, the user manipulates the leg L (or the leg holder **62**) so that the first and second portions **62***a* and **62***b* slide along the base **64** and articulate about the hinge **62***c*. Articulation about the hinge **62***c* causes an angle a of the leg holder **62** to either increase or decrease. The leg holder **62** is preferably configured so that the angle a can be adjusted from approximately 0° to approximately 180°. As a result, the leg L can be moved between a fully extended position and a fully flexed position. As the leg L moves, an incision **128** (e.g., a minimally invasive incision) made on a side of the patient's knee shifts along the leg L. Shifting of the incision **128** enables the surgeon to use the same incision to insert instruments to sculpt both a proximal end of the tibia T and

a distal end of the femur F. As a result, multiple incisions may be avoided, and a size of the incision **128** can be kept small.

[**0201**] In another embodiment, the leg holder **62** may be automated, for example, by the addition of position sensors (e.g., encoders) and a motor controlled by the computer **21** and/or the computer **31**. The motor may enable the leg holder **62** to be fully automated or may simply perform a power-assist function to aid the user in positioning the leg holder **62**. One advantage of fully automating the leg holder **62** is that an automated leg holder can be controlled by the surgical system **10** to autonomously move the leg L to a correct position, which spares the user the difficulty of physically maneuvering the leg L and guessing the correct position for the leg L. For example, a process for controlling an automatic leg holder (or support device) may include placing a first bone (e.g., the tibia T) and/or a second bone (e.g., the femur F) in the leg holder **62** and actuating the leg holder **62** to move the first bone and/or the second bone from a first position to a second position. The process may also include the steps of determining an actual pose of the first bone and/or the second bone (e.g., from the anatomy trackers **43***a* and **43***b*), determining a desired pose of the first bone and/or the second bone, and actuating the leg holder **62** to move the first bone and/or the second bone from the actual pose to the desired pose. As the leg holder **62** moves, the surgical system **10** can monitor the position of the first bone and/or the second bone. When the first bone and/or the second bone is in the desired pose, the process stops. In addition to tracking the position of the first and second bones, the position of the leg holder **62** may be monitored (e.g., using position sensors on the leg holder **62**).

[**0202**] In another embodiment, as shown in **FIG. 14B**, the surgical system **10** includes a leg holder **162**. During a surgical procedure, the leg holder **162** may be mounted on the operating table **102** or other suitable structure. An upper portion of the leg L of the patient rests in the leg holder **162** on a support **164** so that the lower portion of the leg L is freely suspended. Such an approach is advantageous because gravitational forces acting on the suspended portion of the leg L pull open the knee joint to thereby provide greater access to the joint.

[**0203**] In step S**7**, the surgical system **10** prompts the user to attach the anatomy trackers **43***a* and **43***b* to the patient. As shown in **FIG. 25**, the surgical system **10** may also generate a screen **85** to enable the user to optimize positioning of tracked objects with respect to the detection device **41**. For example, the screen **85** may include a representation **85***a* of the detection device **41** and a representation **85***b* of a field of view of the detection device **41**. The screen may also display a representation F**1** of the anatomy tracker **43***a*, a representation T**1** of the anatomy tracker **43***b*, a representation H of the haptic device tracker **45**, and/or a representation of any other trackable element in relation to the field of view **85***a* of the detection device **41**. In one embodiment, each of the representations F**1**, T**1**, and H is displayed in a different color to enable the user to distinguish between each of the tracked objects. In another embodiment, the representations F**1**, T**1**, and H**1** may change to a different color when the tracked object is near a boundary of the field of view of the detection device **41**. In this manner, the user may determine whether tracked objects are sufficiently positioned within the field of view of the detection device **41**.

[**0204**] In one embodiment, once the anatomy trackers **43***a* and **43***b* are attached, a range of motion (ROM) of the knee joint is captured (e.g., by moving the knee joint through the ROM while tracking the anatomy trackers **43***a* and **43***b* with the tracking system **40**). The captured ROM data may be used to assess relative placement of the femoral and tibial implants. For example, the ROM data augmented by registration of the physical patient to the preoperative image data allows the user to plan relative implant positions consistent with a current condition of the patient's soft tissue (e.g., based on disease state, age, weight, current ROM, etc.). In one embodiment, implant depth can be planned so that the installed implants fill the pre-existing joint gap (i.e., the gap existing preoperatively between the tibia T and the femur F) in the knee of the patient. In addition, other important parameters such as, for example, adequate contact, anterior and posterior coverage, and proper relative rotation of the implant pair can be evaluated throughout the ROM of the knee joint. In this way, comprehensive placement planning for both implants can be performed before cutting any bone. The ROM data may also be used (e.g., during the implant planning steps S**10** and S**13**) to display relative positions of the femoral and tibial implants at extension, flexion, and various angles between extension and flexion on the display device **23**.

[**0205**] After the anatomy trackers **43***a* and **43***b* are fixed to the patient, the process proceeds to step S**8** in which the patient's physical anatomy is registered to the representation of the anatomy. For example, the femur F and the tibia T of the patient may be registered in standard fashion using a paired-point/surface match approach based on the femoral and tibial landmarks specified in steps S**3** and S**4**, respectively. The surgical system **10** generates screens to guide the user through the registration process. For example, a screen **86***a* (FIG. **26**) instructs the user to rotate the femur F to find a center of a hip of the leg L. In one embodiment, the surgical system **10** determines the hip center by determining a center of a pivot point of the femur F based on motion of the anatomy tracker **43***a* during the rotation of the femur F. Screens **86***b*, **86***c*, **86***d*, **86***e*, and **86***f* (shown in **FIGS. 27, 28, 29, 30**, and **31**, respectively) instruct the user to point a registration probe to various anatomical landmarks (e.g., medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle, posterior border of anterior cruciate ligament (ACL) attachment, etc.) and to select the landmarks. For example, the user may place a tip of a tracked registration probe on the relevant landmark and select the landmark with a foot pedal or other input device **25**. When the user selects the landmark, the detection device **41** acquires data related to the pose of the registration probe, which is then used to calculate the location of the landmark. Based on the landmark pose data and the landmark designations in the diagnostic images (in steps S**3** and S**4**), the surgical system **10** registers the physical anatomy to the diagnostic images by determining a correspondence between the physical landmarks on the patient and the landmarks in the diagnostic images. The accuracy of this landmark-based registration may be improved by acquiring surface data for the femur F and the tibia T. For example, the surgical system **10** may generate a screen **86***g* (**FIG. 32**) instructing the user to touch points on (or "paint") a surface of a distal end of the femur F with the registration probe. As the user paints the surface (e.g., by inserting a tip of the registration probe through the incision **128**), the surgical system **10** periodically acquires a position of the probe tip and displays the acquired tip positions on the screen **86***g* as dots **900**. For bone surfaces that are overlaid with cartilage, a sharp probe may be used

to pierce the cartilage and collect points on the surface of the bone (as opposed to points on the surface of the cartilage). Similarly, the surgical system **10** generates a screen **86***h* (**FIG. 33**) and instructs the user to paint a surface of a proximal end of the tibia T with the registration probe. As the user paints the surface (e.g., by inserting the probe tip through the incision **128**), the surgical system **10** periodically acquires a position of the probe tip and displays the acquired tip positions on the screen as the dots **900**. As with the femur, a sharp probe may be used to pierce any cartilage so that points on the surface of the bone (as opposed to the surface of the cartilage) are collected. Additionally, a hooked probe may be used to facilitate the collection of points at a posterior margin of the tibial plateau.

[**0206**] In step S**9**, the haptic device **30** is calibrated to establish a geometric relationship between a coordinate frame of reference of the haptic device **30** and the haptic device tracker **45**. If the haptic device tracker **45** is fixed in a permanent position on the haptic device **30**, calibration is not necessary because the geometric relationship between the tracker **45** and the haptic device **30** is fixed and known (e.g., from an initial calibration during manufacture or setup). In contrast, if the tracker **45** can move relative to the haptic device **30** (e.g., if the arm **34** on which the tracker **45** is mounted is adjustable) calibration is necessary to determine the geometric relationship between the tracker **45** and the haptic device **30**. The surgical system **10** initiates the calibration process by generating a screen **87** (shown in **FIG. 34**) instructing the user to calibrate the haptic device **30**. Calibration involves securing the haptic device tracker **45** in a fixed position on the haptic device **30** and temporarily affixing the end effector tracker **47** to the end effector **35**. The end effector **35** is then moved to various positions in a vicinity of the anatomy (e.g., positions above and below the knee joint, positions medial and lateral to the knee joint) while the tracking system **40** acquires pose data for the trackers **47** and **45** relative to the tracking system **40** in each of the positions. In addition, the surgical system **10** determines a pose of the end effector. **35** relative to the haptic device **30** based on data from the position sensors in the arm **33**. Using the acquired data, the surgical system **10** is able to calculate the geometric relationship between the haptic device tracker **45** and a coordinate frame of reference of the haptic device **30**. The end effector tracker **47** may then be removed from the haptic device **30**. During surgery, the surgical system **10** can determine a pose of the tool **50** based on (a) a known geometric relationship between the tool **50** and the end effector **35**, (b) a pose of the end effector **35** relative to the haptic device **30** (e.g., from the position sensors in the arm **33**), (c) the geometric relationship between the haptic device **30** and the haptic device tracker **45** determined during calibration, and (d) the global or gross position of the haptic device **30** (e.g., from the pose of the haptic device tracker **45** relative to the tracking system **40**). The calibration process of step S**9** need not be performed if the haptic device tracker **45** has not moved with respect to the haptic device **30** since the previous calibration and the previously acquired calibration data is still reliable.

[**0207**] In step S**10**, the user plans bone preparation for implanting a first implant on a first bone. In a preferred embodiment, the first bone is the tibia T, the first implant is the tibial component **74**, and bone preparation is planned by selecting a location on a proximal end of the tibia T where the tibial component **74** will be installed. To facilitate implant planning, the surgical system **10** generates a screen **88***b* (shown in **FIG. 35**) that includes various views of representations of the first and second bones (i.e., the tibia T and the femur F, respectively). For example, the screen **88***b* may include a frame **800** showing a three-dimensional rendering, a frame **802** showing a sagittal view, a frame **804** showing a coronal view, and a frame **806** showing a transverse view. Additionally, a frame **807** may display selection buttons and data relative to implant placement and selection, such as, for example, implant size, depth, internal/external angle, varus/valgus angle, flexion angle, etc. Additionally, a mechanical axis of the femur F (e.g., an axis from the hip center or center of the femoral head to the knee center) and/or a mechanical axis of the tibia T (e.g., an axis from the knee center to the ankle center) may be displayed to aid in implant planning. The user can select and display multiple different slices or three-dimensional reconstructions of the images and can overlay a contour representing a surface of the tibia T (or the femur F) on the slice images to facilitate implant planning. In one embodiment, the surgical system **10** proposes an appropriately sized tibial implant and placement location and associates a representation (or implant model) **808***b* of the tibial implant with the representation of the tibia T. To visually aid the user, the surgical system **10** may also superimpose the representation **808***b* of the tibial implant on the representation of the tibia T. The user has the option to modify the proposed placement. For example, the user may change the size, anterior/posterior position, medial/lateral position, and rotations of the implant model **808***b* (e.g., by dragging or adjusting the implant model **808***b* with a mouse). Changes made to the implant model **808***b* in one of the frames causes the implant model **808***b* in the remaining frames to automatically update. When the user completes tibial implant planning, the surgical system **10** stores the chosen location. Implant planning may be repeated and adjusted as desired at any time during the surgical procedure, such as, for example, prior to, during, and/or after bone preparation.

[**0208**] The location of the tibial component **74** may be selected, for example, based on surgical judgment, to generally center the tibial component **74** on the tibial plateau, to position the tibial component **74** on hard bone to avoid subsidence over time, to position the tibial component **74** a desired distance from one or more landmarks, and/or based on a cartilage surface identified by a tracked tool. In one embodiment, the user selects a location for the tibial component **74** by moving the implant model **808***b* (shown in **FIG. 35**) to the general implantation area. Using the transverse view in the frame **806**, the user adjusts the implant model **808***b* rotationally so that the flat side of the implant model **808***b* is approximately parallel to the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) attachment points. An internal/external angle dimension (designated "External") in the frame **807** displays the resulting internal/external angle. Using the coronal view in the frame **804**, the user adjusts the varus/valgus angle of the implant model **808***b*. A varus/valgus angle (designated "Varus") dimension in the frame **807** displays the resulting varus/valgus angle. Using the sagittal view in the frame **802**, the user adjusts the posterior slope of the implant model **808***b*. A flexion angle dimension (designated "Flexion") in the frame **807** displays the resulting flexion angle. The user may adjust a depth of the implant model **808***b* in the tibia T by adjusting a depth bar (designated "Depth") in the frame

807. The user may also change the size of the implant model **808***b* using a size selection box (designated "Size") in the frame **807**. To aid in positioning of the implant model **808***b*, the user may display the mechanical axes using a button (designated "Display Axes") in the frame **807**. The frame **807** may also include a button (designated "Both Implants") to enable the user to display the tibial and femoral implants on the screen **88***b* simultaneously.

[**0209**] In a preferred embodiment, soft tissue in the joint gap of the knee is taken into account when selecting a placement for the tibial component **74**. For example, the first implant (i.e., the tibial component **74**) may be planned so that a top surface of the tibial component **74** is aligned with a top surface of cartilage in the joint gap. Such an approach advantageously preserves the natural configuration of the joint space which may improve implant performance and longevity. In this embodiment, a height of a cartilage surface above the first bone (i.e., the tibia T) is detected, a representation of the first bone and a representation of the height of the cartilage surface are created, and bone preparation for implanting the first implant on the first bone is based at least in part on the detected height of the cartilage surface. For example, the top surface of the cartilage may be detected (or mapped) by placing a tip of a tracked probe at a point on the top surface of the cartilage and selecting the point with a button (designated "Map Point) in the frame **807**. The representation of the height of the cartilage surface may include a numerical representation (e.g., a distance from the first bone to the cartilage surface) and/or a visual representation (e.g., mapped points may be displayed as points **809** in the frame **800**). Several cartilage points may be mapped (e.g., an anterior point, a posterior point, a medial point, etc.). The user aligns at least a portion of the representation of the first implant (i.e., the implant model **808***b*) with the representation of the height of the cartilage surface (i.e., the points **809**), for example, by adjusting the depth of the implant model **808***b* so that the upper edges of the implant model **808***b* align with the mapped cartilage points **809**. In this embodiment, therefore, the surgical system **10** associates the representation of the first implant with the representation of the first bone based at least in part on a detected location of cartilage in a region of the first bone. In this manner, the depth of the tibial component may be selected based on a thickness of the cartilage on the tibial plateau. Thus, the surgical system **10** enables the user to determine a placement of the tibial component **74** that aligns the top surface of the tibial component **74** with the top surface of the cartilage prior to any bone cutting.

[**0210**] If desired, in step S**10**, the user may also preoperatively plan an initial placement of the second implant (i.e., the femoral component **72**) on the second bone (i.e., the femur F). Preferably, however, step **10** includes only preoperative planning of the first implant (i.e., the tibial component **74**). Femoral planning is delayed until after sculpting (step S**11**) and trialing (step S**12**) of the tibia T so that the size, internal/external rotation, and medial/lateral position of the femoral component can be determined based on the position of the tibial trial in relation to the femur F.

[**0211**] Steps S**11** to S**15** encompass the bone preparation process. In step S**11**, the first bone (e.g., the tibia T) is prepared to receive the first implant (e.g., the tibial component **74**) by manipulating the tool **50** to sculpt the first bone. In step S**12**, a trial implant is fitted to the prepared feature on the first bone. In step S**13**, an initial placement of the second implant (e.g., the femoral component) is planned (or a previously planned placement of the second implant may be revisited and adjusted). In step S**14**, the second bone (e.g., the femur F) is prepared to receive the second implant after preparation of the first bone. In step S**15**, a trial implant is fitted to the prepared features on the second bone.

[**0212**] Bone preparation (or sculpting) may be accomplished, for example, using a spherical burr to sculpt or contour the bone so that a shape of the bone substantially conforms to a shape of a mating surface of the implant. The user has the option to prepare either the femur F or the tibia T first. In a preferred embodiment, the tibia T is prepared first (step S**11**), and the tibial trail implant is fitted to the prepared surface of the tibia T (step S**12**). Placement of the femoral component **72** is then planned (step S**13**) followed by preparation of the femur F (step S**14**). Such an approach is advantageous because the user can plan placement of the femoral component **72** based on a physical relationship between the tibial trial implant and the femur F at various flexions of the leg. Additionally, prior to sculpting the tibia T and the femur F, a portion (e.g., a 3 mm thick section) of the medial posterior condyle of the femur F is preferably removed with a sagittal saw. Removing this portion of the posterior condyle reduces the likelihood of bone impingement of the posterior condyle on the tibial component **74** and provides additional workspace in the knee joint.

[**0213**] Throughout surgical procedure, the surgical system **10** monitors movement of the anatomy to detect movement of the anatomy and makes appropriate adjustments to the programs running on the computer **21** and/or the computer **31**. In one embodiment, the surgical system **10** adjusts the representation of the anatomy in response to the detected movement. For example, the surgical system **10** adjusts the representation of the first bone (i.e., the tibia T) in response to movement of the first bone and adjusts the representation of the second bone (i.e., the femur F) in response to movement of the second bone. The surgical system **10** can also adjust a virtual object associated with the anatomy in response to the detected movement of the anatomy. For example, the virtual object may include a virtual boundary that comprises a representation of an implant (e.g., the virtual boundary may correspond to a shape of a surface of the implant). When bone preparation is planned, the surgical system **10** associates the representation of the implant with the representation of the bone on which the implant is to be implanted. During the surgical procedure, the surgical system **10** adjusts the virtual boundary in response to movement of the bone.

[**0214**] In step S**11**, the first bone is prepared to receive the first implant by manipulating the tool **50** to sculpt the first bone. In one embodiment, the tibia T is prepared by forming the medial tibial pocket feature on the proximal end of the tibia T. Upon installation of the tibial component **74**, the medial tibial pocket feature will mate with the surface **74***a* of the tibial component **74** (shown in **FIG. 10B**). As shown in **FIG. 36**, the surgical system **10** displays a screen **89** showing a graphical representation of the tibia T including, for example, an representation **612** of a portion **618** of bone to be removed and a graphical representation of the tool **50** showing a tool tip **616***a* and a tool shaft **616***b*. The screen **89** may optionally display a position of the opposite bone (i.e., the second bone or femur F) to guide the user in avoiding

accidental cutting of a surface of the opposite bone. The portion **618** of bone to be removed is preferably colored a different color from the surrounding bone. For example, the portion **618** may be colored green while the surrounding bone is colored white. The haptic device **30** enters the approach mode in which a haptic object (e.g., the haptic object **300** shown in **FIG. 1**, the haptic object **310** shown in **FIG. 9**) in the form of an approach path assists the user in guiding the tip of the tool **50** through the incision **128** and toward the feature of interest on the patient (i.e., the portion of bone on the patient's anatomy corresponding to the portion **618** graphically represented on the screen **89**). In the approach mode, the tool **50** is disabled to avoid accidental cutting as the tool **50** traverses the incision **128** and is navigated to the feature of interest. The surgical system **10** automatically places the haptic device **30** in the haptic (or burring) mode, for example, when the tip of the tool **50** approaches a predefined point related to the feature of interest. When the haptic device **30** is placed in the haptic mode, the surgical system **10** also initiates an occlusion detection algorithm.

[**0215**] The occlusion detection algorithm is a safety feature that turns off power to the tool **50** if either the haptic device tracker **45** or one of the anatomy trackers **43***a* or **43***b* is at any time occluded while the haptic device **30** is in the haptic (or burring) mode. If an occluded state is detected, the occlusion detection algorithm may also cause a warning message to be displayed on the display device **23**, an audible alarm to sound, and/or power to the tool **50** to be shut off. Thus, the occlusion detection algorithm prevents the tool **50** from damaging the anatomy when the tracking system **40** is not able to track a relative position of the tool **50** and the anatomy. For example, in one embodiment, if the occlusion detection algorithm detects an occluded state, the surgical system **10** determines whether the tool **50** is touching a haptic boundary of a haptic object. If the tool **50** is not in contact with a haptic boundary, the occlusion detection algorithm places the haptic device **30** in the free mode so that the tool **50** will move with the patient and, if necessary, can be withdrawn from the patient. When the occluded state ends (e.g., when an occluded tracker again becomes visible), the surgical system **10** places the haptic device **30** in the approach mode so that the user may resume the procedure. In contrast, if the surgical system **10** determines that the tool **50** is touching the haptic boundary during the occluded state, the occlusion detection algorithms waits for a predetermined period of time (e.g., 1 second) to see if the occluded tracker becomes visible. If the haptic device tracker **45** and the anatomy trackers **43***a* and **43***b* all become visible within the predetermined period of time, the haptic (or burring) mode is resumed. Otherwise, the haptic device **30** is placed in the free mode so that the tool **50** will move with the patient and, if necessary, can be withdrawn from the patient. As before, when the occluded state ends (e.g., when an occluded tracker again becomes visible), the surgical system **10** places the haptic device **30** in the approach mode so that the user may resume the procedure.

[**0216**] Once the haptic device **30** enters the haptic mode, the user may proceed with bone sculpting. To sculpt the bone, the user manipulates the haptic device **30** by moving a portion of the haptic device **30** (e.g., the tool **50**) in a region of the anatomy (e.g., the bone). As best seen in **FIG. 37**, as the user removes material from the bone with the tool **50**, the surgical system **10** updates the image of the tibia T on the screen **89** to show a depth to which bone has been removed. During the bone removal process, the haptic device **30** imparts force feedback to the user, for example, based on a haptic object (e.g., the haptic object **206** in **FIG. 9**) having a shape and volume corresponding to the portion **618** of bone to be removed. For the medial tibial surface feature, a boundary of the haptic object may substantially correspond, for example, to the surface **74***a* (shown in **FIG. 10***b*) of the tibial component **74** that will mate with the sculpted surface of the tibia T. The force feedback encourages the user to keep the tip of the tool **50** within the boundaries of the haptic object. For example, the force feedback may constrain the tool **50** against penetrating at least a portion of the haptic object, such as a virtual boundary. Although the haptic object is virtual and the tool **50** moves in physical space, the surgical system **10** associates the anatomy, the haptic object, and the haptic device **30** with the representation of the anatomy. Thus, the haptic object and the tool **50** are both in registration with the physical anatomy of the patient. As a result, the virtual haptic object is able to bound or constrain movement of the physical tool **50**.

[**0217**] In addition to haptically guiding the user in the bone sculpting process, the surgical system **10** may also provide visual feedback to the user. For example, when the tool **50** reaches a desired cutting depth in a particular location of the portion **618**, the color of the particular location may change from green to white to indicate that no more bone should be removed from that location. Similarly, if the tool **50** cuts beyond the desired cutting depth, the color of the particular location may change from white to red to alert the user that the cut is too deep. To further reduce the possibility of damage to healthy tissue, the surgical system **10** may also be programmed to disable power to the tool **50** should the user cut too deeply. When sculpting of the medial tibial pocket feature is complete, the user may signal (e.g., using a foot pedal or other input device **25**) that he is ready to proceed to forming the next feature or that he wishes to withdraw the tool **50**. The tool **50** may be withdrawn at any time during the sculpting process even if the feature is not complete. For example, the user may wish to withdraw the tool **50** to replace the tool tip, irrigate the surgical site, perform a trail reduction, revisit implant planning, address a problem that has arisen, or the like. If the user signals that he wants to withdraw the tool **50**, the occlusion detection algorithm is halted and the haptic device **30** is placed in the free mode to enable withdrawal of the tool **50**.

[**0218**] Step S**12** is a trial reduction process in which the first implant (i.e., the tibial component **74**) or a trial implant (e.g., a tibial trial) is fitted to the first bone (i.e., the prepared medial tibial pocket feature on the tibia T). The user assesses the fit of the tibial component or the tibial trial and may make any desired adjustments, such as, for example, repeating implant planning and/or bone sculpting to achieve an improved fit.

[**0219**] In step S**13**, the user plans bone preparation for implanting a second implant on a second bone after preparing the first bone. In a preferred embodiment, the second bone is the femur F, the second implant is the femoral component **72**, and bone preparation is planned by selecting a location on a distal end of the femur F where the femoral component **72** will be installed. If the femoral component **72** has been previously planned (e.g., in step S**10**), the prior placement may be revisited and adjusted if desired. As in

step S10, the surgical system **10** facilitates implant planning by generating a screen **88***a* (shown in **FIG. 38**). The screen **88***a* is similar to the screen **88***b* (shown in **FIG. 35**) used for planning of the tibial component **74** except the frames **800**, **802**, **804**, **806**, and **807** include images, data, and selection buttons relevant to placement of the femoral component **72**, including a representation (or implant model) **808***b* of the second implant (i.e., the femoral component **72**).

[**0220**] The location of the femoral component **72** may be determined, for example, relative to the position of pre-existing implants and surrounding structures. These points may be mapped using a tracked tool in the same manner as the cartilage points in step S10 above. The mapped points may include points on anatomic structures in the joint (e.g., bone, nerves, soft tissue, etc.) and/or points on pre-existing implants in the joint (e.g., edges, corners, surfaces, verification features, divots, grooves, centerline markings, etc.). The pre-existing implants may include, for example, the first implant (i.e., the tibial component **74**), a trial implant (e.g., the tibial trial), and/or an existing implant from a prior surgery. The points may be selected with the leg L at various angles from full extension to full flexion. For example, points may be mapped with the leg L in full extension, at 90°, and in full flexion. In one embodiment, the knee joint is moved to a first position (e.g., one of flexion and extension), the user identifies a first point corresponding to a first location in the joint when the joint is in the first position, the knee joint is moved to a second position (e.g., the other of flexion and extension), and the user identifies a second point corresponding to a second location in the joint when the joint is in the second position. The surgical system **10** displays the first and second points in the frame **800** on the screen **88***a* as points **810**. The points **810** aid the user in visualizing placement of the second implant (i.e., the femoral component **72**). Thus, the user is able to plan bone preparation for implanting the second implant on the second bone based at least in part on the first and second points.

[**0221**] In one embodiment, the size and position of the femoral component **72** are determined by mapping a first point at a centerline on an anterior edge of the tibial trial implant with the leg in extension and a second point at the centerline on the anterior edge of the tibial trial implant with the leg in flexion. The extension point is used to size the femoral component **72**. For example, the size of the femoral component **72** may be selected so that the tibial component **74** will not ride off an anterior edge of the femoral component **72** as the knee moves into extension. The flexion and extension points together are used to determine the internal/external rotation of the femoral component **72** to ensure that the femoral component **72** properly rides on the tibial component **74** (e.g., based on the patient's natural range of motion and joint kinematics). For example, a centerline of a representation of the second implant (e.g., a representation of the keel **72***c* of the femoral component **72**) may be aligned with the flexion and extension points. Optionally, a point on the posterior "cut" edge may be used to determine the posterior placement of the femoral component **72**. In this embodiment, the user selects a location for the femoral component **72** by moving the implant model **808***a* (shown in **FIG. 38**) to the general implantation area. Using the transverse view in the frame **806**, the user adjusts the implant model **808***a* rotationally so that a centerline of the implant model **808***a* aligns with the mapped points **810** representing the centerline of the tibial trial implant in extension and flexion. An internal/external angle dimension (designated "External") in the frame **807** displays the resulting internal/external angle. Using the coronal view in the frame **804**, the user adjusts the varus/valgus angle of the implant model **808***a*. A varus/valgus (designated "Valgus") angle dimension in the frame **807** displays the resulting varus/valgus angle. Using the sagittal view in the frame **802**, the user adjusts the posterior rotation of the implant model **808***a*. A flexion angle dimension (designated "Flexion") in the frame **807** displays the resulting flexion angle. In one embodiment, the posterior rotation is adjusted so that the stem of the femoral component **72** is within a range of approximately 50 to approximately 80 of the anatomical axis of the bone image. The user may adjust a distal depth of the implant model **808***a* in the femur F by adjusting a depth bar (designated "Depth") in the frame **807**. The user may also change the size of the implant model **808***a* using a size selection box (designated "Size") in the frame **807**. In this manner, the representation of the second implant (the implant model **808***a*) is associated with the representation of the second bone (i.e., the femur F) based at least in part on a detected location of the first implant on the first bone (i.e., the tibia T).

[**0222**] In step S14, the second bone is prepared to receive the second implant by manipulating the tool **50** to sculpt the second bone. In one embodiment, the femur F is prepared by forming the medial femoral surface, post, and keel features on the distal end of the femur F. Upon installation of the femoral component **72**, the medial femoral surface, post, and keel features will mate with a surface **72***a*, a post **72***b*, and a keel **72***c*, respectively, of the femoral component **72** (shown in **FIG. 10A**). Preparation of the femoral features is substantially similar to the preparation of the medial tibial surface feature. As shown in **FIG. 39**, the surgical system **10** displays a screen **91** showing a graphical representation of the femur F. As with the screen **89** for tibia preparation, the screen **91** includes the representation **612** of the portion **618** of bone to be removed and a graphical representation of the tool **50** showing the tool tip **616***a* and a tool shaft **616***b*. The screen **91** may optionally display a position of the opposite bone (i.e., the tibia T) to guide the user in avoiding accidental cutting of a surface of the opposite bone. As before, the portion **618** of bone to be removed is preferably colored a different color from the surrounding bone. The haptic device **30** enters the approach mode in which a haptic object (e.g., the haptic object **300** in **FIG. 1**, the haptic object **310** in **FIG. 9**) in the form of an approach path assists the user in guiding the tip of the tool **50** through the incision **128** and toward the feature of interest on the patient (i.e., the portion of bone on the patient's anatomy corresponding to the portion **618** graphically represented on the screen **91**). The surgical system **10** automatically places the haptic device **30** in the haptic (or burring) mode, for example, when the tip of the tool **50** approaches a predefined point related to the feature of interest. When the haptic device **30** is placed in the haptic mode, the surgical system **10** also initiates the occlusion detection algorithm.

[**0223**] Once the haptic device **30** enters the haptic mode, the user may proceed with bone sculpting. As shown in **FIG. 39**, as the user removes bone with the tool **50**, the surgical system **10** updates the image of the femur F on the screen **91** to show a depth to which bone has been removed. During the bone removal process, the haptic device **30** imparts force feedback to the user, for example, based on a haptic object (e.g., a haptic object **208** shown in **FIG. 9**) having a shape

and volume corresponding to the portion **618** of bone to be removed. For the medial femoral surface feature, a boundary of the haptic object may substantially correspond, for example, to the surface **72***a* (shown in **FIG. 10A**) of the femoral component **72** that will mate with the sculpted surface of the femur F. The force feedback encourages the user to keep the tip of the tool **50** within the boundaries of the haptic object.

[0224] During sculpting, the user may desire to change the tool **50**. For example, in one embodiment, the user uses a 6 mm burr to form most of the medial femoral surface feature and a 2 mm to sculpt the "corners" (e.g., regions where a vertical wall of the feature transitions to a horizontal bottom of the feature). To replace the burr, the user signals that he wants to withdraw the tool **50**. In response, the occlusion detection algorithm is halted and the haptic device **30** is placed in the free mode to enable withdrawal of the tool **50**. Once the burr has been replaced, the haptic device **30** may be placed in the approach mode to enable the user to direct the tool **50** to the surgical site to finish forming the medial femoral surface feature. In a preferred embodiment, prior to recommencing sculpting, the user touches the tool **50** (or a tracked probe) to a mark that was placed on the bone (e.g., the femur F or the tibia T) during the initial registration in step S**8**. The mark functions as a check point that enables the surgical system **10** to verify proper system configuration. For example, the check point can be used to verify that the tracking system **40** is properly configured (e.g., trackers still properly aligned relative to the anatomy, not blocked or occluded, etc.), that that the tool **50** is correctly installed (e.g., property seated, shaft not bent, etc.), and/or that any other object is properly mounted, installed, set up, etc. If the check reveals a problem with the system configuration (e.g., one of the trackers was bumped by the user during the tool change and is now misaligned), registration (step S**8**) must be repeated. This check point verification may be performed anytime the user desires to validate the system configuration such as when the tool **50** is withdrawn from and then reinserted into the patient. When sculpting of the medial femoral surface feature is complete, the user may signal (e.g., using a foot pedal or other input device **25**) that he is ready to proceed to forming the medial femoral post feature. In one embodiment, prior to forming the medial post feature, the user replaces the 2 mm burr used to form the corners of the medial femoral surface feature with a 4 mm burr.

[0225] The process for sculpting the medial femoral post feature is substantially similar to the process for sculpting the medial femoral surface feature. As with the femoral surface feature, the surgical system **10** displays the screen **91** (shown in **FIG. 39**) showing the graphical representation of the femur F, the representation **612** of the portion **618** of bone to be removed, a representation of the tool **50** showing a representation the tool tip **616***a* and a representation of the tool shaft **616***b*, and optionally a representation of the opposite bone (i.e., the tibia T). As before, the portion **618** of bone to be removed is preferably colored a different color from the surrounding bone. In one embodiment, the surgical system **10** displays only the representation of the tip **616***a* of the tool **50** in the screen **91**. However, due to the criticality of an approach angle of the tool **50** in forming the post and keel features, the surgical system **10** preferably indicates an allowable angle of inclination of the shaft of the tool **50** when the post and keel features are being sculpted. For example, the representation of the shaft **616***b* may be displayed so that the user is able to see how the shaft **616***b* is oriented with respect to the anatomy. Thus, the user can determine whether the shaft is rubbing against a previously sculpted bone wall (or other object) as the user sculpts deeper portions of the femoral features. A numerical value of a tool angle (e.g., an angle of inclination) may also be shown the screen **91**. The surgical system **10** may also include a haptic object shaped so as to constrain an angle of the shaft of the tool **50** to a predetermined value. In one embodiment, the predetermined value is such that the shaft of the tool **50** remains substantially perpendicular to a plane of bone into which the tool **50** is cutting. For example, the predetermined value may be in a range of about 80° to about 90° from the plane of bone into which the tool **50** is cutting. The screen **91** may also include a graphical depiction of the haptic object that constrains the shaft and may change the color of the haptic object (e.g., to red) if the tool angle exceeds the predetermined value. Additionally or alternatively, the tool **50** may include a sleeve disposed about the shaft and/or the tip of the tool **50** that prevents the rotating shaft and/or tip from coming into direct contact with bone.

[0226] The haptic device **30** enters the approach mode in which a haptic object (e.g., the haptic object **300** in **FIG. 1**, the haptic object **310** shown in **FIG. 9**) in the form of an approach path assists the user in guiding the tip of the tool **50** toward the feature of interest on the patient (i.e., the portion of bone on the patient's anatomy corresponding to the portion **618** graphically represented on the screen **91**). The surgical system **10** automatically places the haptic device **30** in the haptic (or burring) mode, for example, when the tip of the tool **50** approaches a predefined point related to the feature of interest. If the occlusion detection algorithm was previously halted (e.g., to withdraw the tool **50** after formation of the femoral surface feature), the surgical system **10** initiates the occlusion detection algorithm when the haptic device **30** enters the haptic mode.

[0227] Once the haptic device **30** enters the haptic mode, the user may proceed with bone sculpting. As the user removes bone with the tool **50**, the surgical system **10** updates the image of the femur F on the screen **91** to show a depth to which bone has been removed. During the bone removal process, the haptic device **30** imparts force feedback to the user, for example, based on a haptic object having a shape and volume corresponding to the portion **618** of bone to be removed. For the medial femoral post feature, a boundary of the haptic object may substantially correspond, for example, to a surface of the post **72***b* (shown in **FIG. 10A**) of the femoral component **72** that will mate with the sculpted surface of the femur F. When the medial femoral post feature is complete, the user may signal (e.g., using a foot pedal or other input device **25**) that he is ready to proceed to forming the medial femoral keel feature. In one embodiment, prior to forming the keel feature, the user replaces the 4 mm burr with a straight burr. As discussed above in connection with the corners of the medial femoral surface feature, to replace the burr, the user signals that he needs to withdraw the tool **50**. In response, the occlusion detection algorithm is halted and the haptic device **30** is placed in the free mode to enable withdrawal of the tool **50**. Once the burr has been replaced, the user may proceed with forming the medial femoral keel feature. Preferably, the user performs the above-described check point verification prior to recommencing bone sculpting.

[0228] The process for sculpting the medial femoral keel feature is substantially similar to the process for sculpting the medial femoral surface and post features. As with the femoral surface and post features, the surgical system **10** displays the screen **91** (shown in **FIG. 39**) showing the graphical representation of the femur F, the representation **612** of the portion **618** of bone to be removed, a graphical representation of the tool **50** showing the tool tip **616***a* and a tool shaft **616***b*, and optionally a representation of the opposite bone (i.e., the tibia T). As before, the portion **618** of bone to be removed is preferably colored a different color from the surrounding bone. Additionally, as discussed above in connection with the medial femoral post feature, the screen **91** may include features that enable the user to monitor tool angle to avoid damaging surrounding bone with the rotating shaft of the tool **50**.

[0229] The haptic device **30** enters the approach mode in which a haptic object (e.g., the haptic object **300** in **FIG. 1**, the haptic object **310** shown in **FIG. 9**) in the form of an approach path assists the user in guiding the tip of the tool **50** through the incision **128** and toward the feature of interest on the patient (i.e., the portion of bone on the patient's anatomy corresponding to the portion **618** graphically represented on the screen **91**). The surgical system **10** automatically places the haptic device **30** in the haptic (or burring) mode, for example, when the tip of the tool **50** approaches a predefined point related to the feature of interest. When the haptic device **30** enters the haptic mode, the surgical system **10** also initiates the occlusion detection algorithm. Once the haptic device **30** enters the haptic mode, the user may proceed with bone sculpting. As the user removes bone with the tool **50**, the surgical system **10** updates the image of the femur F on the screen **91** to show a depth to which bone has been removed. During the bone removal process, the haptic device **30** imparts force feedback to the user, for example, based on a haptic object having a shape and volume corresponding to the portion **618** of bone to be removed. For the medial femoral keel feature, a boundary of the haptic object may substantially correspond, for example, to a surface of the keel **72***c* (shown in **FIG. 10A**) of the femoral component **72** that will mate with the sculpted surface of the femur F. When the medial femoral keel feature is complete, the user may signal (e.g., using a foot pedal or other input device **25**) that he is ready to withdraw the tool **50** from the patient. In response, the surgical system **10** halts the occlusion detection algorithm and places the haptic device **30** in the free mode to enable retraction of the tool **50**.

[0230] Step S**15** is a trial reduction process in which the second implant (i.e., the femoral component **72**) or a trial implant (e.g., a femoral trial) is fitted to the prepared medial femoral surface, post, and keel features on the femur F. The user assesses the fit of the femoral component **72** or the femoral trial and may make any desired adjustments, such as, for example, repeating implant planning and/or bone sculpting to achieve an improved fit. In step S**15**, adjustments may also be made to the tibia T. To facilitate trial reduction, the surgical system **10** may generate a screen (not shown) that graphically represents the tracked movement of the femur F and the tibia T and displays measurements, such as, for example, flexion, varus/valgus, and internal/external rotation angles. Additionally, the femoral and/or tibial trial implants may include intrinsic features (e.g., divots, markings, etc.) that can be touched with a tracked probe after the trial implant is fitted to the bone to enable the surgical system **10** to verify placement of the trial implant. The intrinsic features may also be used to key a position of one implant to another implant (e.g., in the case of a modular implant). When the user is satisfied with the fit of the trial implants, the user may proceed with installation of the femoral component **72** and the tibial component **74** and completion of the surgical procedure.

[0231] Thus, embodiments of the present invention provide a haptic guidance system and method that may replace direct visualization in minimally invasive surgery, spare healthy bone in orthopedic joint replacement applications, enable intraoperative adaptability and planning, and produce operative results that are sufficiently predictable, repeatable, and/or accurate regardless of surgical skill level.

[0232] Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only.

What is claimed is:

1. A surgical apparatus, comprising:

a surgical device configured to be manipulated by a user to perform a procedure on a patient; and

a computer system programmed:

to implement control parameters for controlling the surgical device to provide at least one of haptic guidance to the user and a limit on user manipulation of the surgical device, based on a relationship between an anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the surgical device, and

to adjust the control parameters in response to movement of the anatomy during the procedure.

2. The surgical apparatus of claim 1, wherein the surgical device includes an arm, a surgical tool coupled to the arm, and an interface associated with at least one of the arm and the surgical tool.

3. The surgical apparatus of claim 2, wherein the interface includes a first part configured to enable the user to change a configuration of the arm and a second part configured to enable the user to move the surgical tool relative to the arm.

4. The surgical apparatus of claim 3, wherein the first part comprises a joint of the arm and the second part comprises at least one of a distal end of the arm and the surgical tool.

5. The surgical apparatus of claim 2, wherein the computer system is programmed to control the surgical device to generate at least one of a force, a torque, and vibration based on a position of the surgical tool relative to at least one of a virtual object associated with the anatomy, a parameter relative to the anatomy, and the anatomy.

6. The surgical apparatus of claim 1, wherein the surgical device includes a feedback mechanism; and the computer system is configured to control the feedback mechanism to communicate information to the user, while the user manipulates the surgical device, about a location of the portion of the surgical device relative to at least one of a virtual object associated with the anatomy, a parameter relative to the anatomy, and the anatomy.

7. The surgical apparatus of claim 6, wherein the feedback mechanism includes at least one motor for producing at least one of a force, a torque, and vibration.

8. The surgical apparatus of claim 1, wherein the surgical device includes at least one feedback mechanism configured to supply feedback to the user manipulating the surgical device; and the computer system is programmed to control the at least one feedback mechanism to provide haptic guidance to the user, while the user manipulates the surgical device, based on the relationship between the anatomy of the patient and the at least one of a position, an orientation, a velocity, and an acceleration of the portion of the surgical device.

9. The surgical apparatus of claim 8, wherein the at least one feedback mechanism includes a motor configured to supply force feedback opposing the user's manipulation of the surgical device.

10. The surgical apparatus of claim 9, wherein the computer system is programmed to permit the user to overcome the force feedback and move the surgical device to a desired location.

11. The surgical apparatus of claim 8, wherein the at least one feedback mechanism includes an oscillator for producing vibration.

12. The surgical apparatus of claim 1, wherein the computer system is programmed to control the surgical device using impedance control.

13. The surgical apparatus of claim 1, wherein the computer system is programmed to determine the control parameters based at least in part on a virtual object associated with the anatomy.

14. The surgical apparatus of claim 1, wherein the computer system is programmed to adjust a virtual object associated with the anatomy in response to movement of the anatomy during the procedure by monitoring detected movement of the anatomy and then adjusting the virtual object in response to the detected movement.

15. The surgical apparatus of claim 1, further comprising a detection device for determining a pose of an object.

16. The surgical apparatus of claim 15, wherein the detection device is mounted to the surgical device.

17. The surgical apparatus of claim 16, wherein the detection device is moveable from a first position to a second position relative to the surgical device.

18. The surgical apparatus of claim 16, wherein the detection device is fixed in position with respect to the surgical device.

19. The surgical apparatus of claim 15, further comprising at least one trackable element detectable by the detection device and configured to be attached to an object to be tracked.

20. The surgical apparatus of claim 19, wherein the at least one trackable element comprises an array of markers having a unique geometric arrangement and having a known geometric relationship to the object when the at least one trackable element is attached to the object.

21. The surgical apparatus of claim 19, wherein the computer system is programmed to alert the user if the detection device is unable to detect the at least one trackable element during the procedure.

22. The surgical apparatus of claim 19, wherein the at least one trackable element includes a fixation device for attachment to the anatomy.

23. The surgical apparatus of claim 22, wherein the fixation device includes at least one bone pin.

24. The surgical apparatus of claim 19, wherein the at least one trackable element is disposed on the surgical device.

25. The surgical apparatus of claim 24, wherein the at least one trackable element is moveable between a first position and a second position relative to the surgical device.

26. The surgical apparatus of claim 24, wherein the at least one trackable element is fixed in position with respect to the surgical device.

27. The surgical apparatus of claim 19, wherein the surgical device includes an arm configured to engage a surgical tool, and wherein the at least one trackable element is configured to be disposed on at least one of a distal end of the arm and the surgical tool.

28. The surgical apparatus of claim 19, wherein the at least one trackable element is coupled to a probe.

29. The surgical apparatus of claim 19, wherein the at least one trackable element includes a feature for verifying a calibration of a probe.

30. The surgical apparatus of claim 29, wherein the feature comprises a divot.

31. The surgical apparatus of claim 15, wherein the detection device is configured to be connected to an object to be tracked.

32. The surgical apparatus of claim 31, wherein the detection device includes a fixation device for attachment to a bone of the patient.

33. A surgical apparatus, comprising:

a haptic device configured to be manipulated by a user to perform a procedure on a patient, the haptic device including at least one feedback mechanism configured to supply feedback to the user manipulating the haptic device; and

a computer system programmed to implement control parameters for controlling the at least one feedback mechanism to provide haptic guidance to the user, while the user manipulates the haptic device, based on a relationship between an anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the haptic device.

34. The surgical apparatus of claim 33, wherein the computer system is programmed to:

adjust the control parameters in response to movement of the anatomy during the procedure.

35. The surgical apparatus of claim 33, wherein the haptic device includes an arm, a surgical tool coupled to the arm, and an interface associated with at least one of the arm and the surgical tool.

36. The surgical apparatus of claim 34, wherein the interface includes a first part configured to enable the user to change a configuration of the arm and a second part configured to enable the user to move the surgical tool relative to the arm.

37. The surgical apparatus of claim 36, wherein the first part comprises a joint of the arm and the second part comprises at least one of a distal end of the arm and the surgical tool.

38. The surgical apparatus of claim 34, wherein the computer system is programmed to control the haptic device to generate at least one of a force, a torque, and vibration based on a position of the surgical tool relative to at least one of a virtual object associated with the anatomy, a parameter relative to the anatomy, and the anatomy.

39. The surgical apparatus of claim 33, wherein the computer system is configured to control the feedback mechanism to communicate information to the user, while the user manipulates the haptic device, about a location of the portion of the haptic device relative to at least one of a virtual object associated with the anatomy, a parameter relative to the anatomy, and the anatomy.

40. The surgical apparatus of claim 33, wherein the feedback mechanism includes at least one motor for producing at least one of a force, a torque, and vibration.

41. The surgical apparatus of claim 33, wherein the at least one feedback mechanism includes a motor configured to supply force feedback opposing the user's manipulation of the haptic device.

42. The surgical apparatus of claim 41, wherein the computer system is programmed to permit the user to overcome the force feedback and move the haptic device to a desired location.

43. The surgical apparatus of claim 33, wherein the computer system is programmed to control the haptic device using impedance control.

44. The surgical apparatus of claim 33, wherein the computer system is programmed to determine the control parameters based at least in part on a virtual object associated with the anatomy.

45. The surgical apparatus of claim 33, wherein the computer system is programmed to adjust a virtual object associated with the anatomy in response to movement of the anatomy during the procedure by monitoring detected movement of the anatomy and then adjusting the virtual object in response to the detected movement.

46. The surgical apparatus of claim 33, further comprising a detection device for determining a pose of an object.

47. The surgical apparatus of claim 46, wherein the detection device is mounted to the haptic device.

48. The surgical apparatus of claim 47, wherein the detection device is moveable from a first position to a second position relative to the haptic device.

49. The surgical apparatus of claim 47, wherein the detection device is fixed in position with respect to the haptic device.

50. The surgical apparatus of claim 46, further comprising at least one trackable element detectable by the detection device and configured to be attached to an object to be tracked.

51. The surgical apparatus of claim 50, wherein the at least one trackable element comprises an array of markers having a unique geometric arrangement and having a known geometric relationship to the object when the at least one trackable element is attached to the object.

52. The surgical apparatus of claim 50, wherein the computer system is programmed to alert the user if the detection device is unable to detect the at least one trackable element during the procedure.

53. The surgical apparatus of claim 50, wherein the at least one trackable element includes a fixation device for attachment to the anatomy.

54. The surgical apparatus of claim 53, wherein the fixation device includes at least one bone pin.

55. The surgical apparatus of claim 50, wherein the at least one trackable element is disposed on the haptic device.

56. The surgical apparatus of claim 55, wherein the at least one trackable element is moveable between a first position and a second position relative to the haptic device.

57. The surgical apparatus of claim 55, wherein the at least one trackable element is fixed in position with respect to the haptic device.

58. The surgical apparatus of claim 50, wherein the haptic device includes an arm configured to engage a surgical tool, and wherein the at least one trackable element is configured to be disposed on at least one of a distal end of the arm and the surgical tool.

59. The surgical apparatus of claim 50, wherein the at least one trackable element is coupled to a probe.

60. The surgical apparatus of claim 50, wherein the at least one trackable element includes a feature for verifying a calibration of a probe.

61. The surgical apparatus of claim 60, wherein the feature comprises a divot.

62. The surgical apparatus of claim 46, wherein the detection device is configured to be connected to an object to be tracked.

63. The surgical apparatus of claim 62, wherein the detection device includes a fixation device for attachment to a bone of the patient.

64. A surgical method, comprising the steps of:

creating a representation of an anatomy of a patient;

associating the anatomy and a surgical device with the representation of the anatomy;

manipulating the surgical device to perform a procedure on a patient by moving a portion of the surgical device in a region of the anatomy;

controlling the surgical device to provide at least one of haptic guidance and a limit on manipulation of the surgical device, based on a relationship between the representation of the anatomy and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the surgical device; and

adjusting the representation of the anatomy in response to movement of the anatomy during the procedure.

65. The method of claim 64, further comprising the step of:

defining a parameter relative to the representation of the anatomy.

66. The method of claim 65, wherein the parameter comprises a distance.

67. The method of claim 65, further comprising the step of:

controlling the surgical device to provide the at least one of haptic guidance and a limit on manipulation of the surgical device based on the parameter and the at least one of a position, an orientation, a velocity, and an acceleration of the portion of the surgical device.

68. The method of claim 64, further comprising the step of:

associating a virtual object with the representation of the anatomy.

69. The method of claim 68, further comprising the step of:

controlling the surgical device to provide the at least one of haptic guidance and a limit on manipulation of the surgical device based on the virtual object and the at least one of a position, an orientation, a velocity, and an acceleration of the portion of the surgical device.

70. The method of claim 68, further comprising the steps of:

monitoring a position of the anatomy to detect movement of the anatomy; and

adjusting the virtual object in response to the detected movement.

71. The method of claim 68, wherein the step of controlling the surgical device includes constraining the portion of the surgical device against penetrating at least a portion of the virtual object.

72. The method of claim 68, wherein at least a portion of the virtual object represents a portion of material to be removed from the anatomy.

73. The method of claim 68, wherein a shape of at least a portion of the virtual object substantially corresponds to a shape of a surface of an implant to be fitted to the anatomy.

74. The method of claim 68, further comprising the step of:

superimposing a representation of the virtual object on the representation of the anatomy.

75. The method of claim 68, wherein the virtual object represents a pathway from a first position to a second position.

76. The method of claim 75, wherein second position includes a target region of the anatomy.

77. The method of claim 75, further comprising the steps of:

activating the virtual object so that movement of the portion of the surgical device is constrained along the pathway; and

deactivating the virtual object when the portion of the surgical device reaches the second position.

78. The method of claim 77, further comprising the step of:

deactivating the virtual object to enable the portion of the surgical device to deviate from the pathway.

79. The method of claim 64, wherein the surgical device includes an arm, a surgical tool coupled to the arm, and an interface associated with at lest one of the arm and the surgical tool.

80. The method of claim 79, wherein the interface includes a first part configured to enable a user to change a configuration of the arm and a second part configured to enable the user to move the surgical tool relative to the arm.

81. The method of claim 79, further comprising the step of:

manipulating the interface to simultaneously change a configuration of the arm and move the surgical tool relative to the arm.

82. The method of claim 64, wherein the step of controlling the surgical device includes controlling a feedback mechanism to generate at least one of a force, a torque, and vibration.

83. The method of claim 64, wherein the step of controlling the surgical device includes generating force feedback that opposes a user's manipulation of the surgical device.

84. The method of claim 83, wherein the force feedback is determined based on a proximity of the portion of the surgical device to a virtual boundary associated with the representation of the anatomy.

85. The method of claim 83, wherein a magnitude of the force feedback increases as the portion of the surgical device approaches a virtual boundary associated with the representation of the anatomy.

86. The method of claim 64, wherein the haptic guidance communicates information to a user manipulating the surgical device about a position of the portion of the surgical device relative to at least one of a virtual boundary associated with the representation of the anatomy, a parameter relative to the representation of the anatomy, and the anatomy.

87. The method of claim 64, further comprising the step of:

offsetting a force feedback curve for controlling the surgical device by a desired value.

88. The method of claim 87, further comprising the steps of:

storing the desired value; and

associating the desired value with a user.

89. The method of claim 87, wherein the step of offsetting the force feedback curve includes increasing or decreasing a size of a haptic object.

90. The method of claim 87, wherein the step of offsetting the force feedback curve includes increasing or decreasing a size of a representation of a surgical tool coupled to the surgical device.

91. The method of claim 64, further comprising the steps of:

monitoring a position of the surgical device.

92. The method of claim 64, further comprising the steps of:

creating a representation of a surgical tool coupled to the surgical device.

93. The method of claim 92, further comprising the steps of:

updating the representation of the surgical tool as a user manipulates the surgical device to perform the procedure on the patient.

94. The method of claim 92, wherein the representation of the surgical tool includes a representation of at least one of a tip of the surgical tool and a shaft of the surgical tool.

95. The method of claim 92, further comprising the step of:

indicating an allowable angle of inclination of a shaft of the surgical tool.

96. The method of claim 64, further comprising the steps of:

creating a representation of at least a portion of material to be removed from the anatomy;

manipulating the surgical device to remove material from the anatomy; and

creating a representation of the material removed by the surgical device.

97. The method of claim 96, further comprising the steps of:

creating the representation of the portion of material to be removed in a first color;

creating the representation of the material removed by the surgical device in a second color when a desired amount of material has been removed; and

creating the representation of the material removed by the surgical device in a third color when the material removed by the surgical device exceeds the desired amount of material.

98. The method of claim 64, further comprising the step of:

generating at least one display configured to guide a user manipulating the surgical device through the procedure.

99. The method of claim 98, wherein the at least one display prompts the user to perform a task.

100. A surgical method, comprising the steps of:

creating a representation of an anatomy of a patient;

associating the anatomy and a haptic device with the representation of the anatomy;

manipulating the haptic device to perform a procedure on a patient by moving a portion of the haptic device in a region of the anatomy; the haptic device including at least one feedback mechanism configured to supply feedback during manipulation; and

controlling the at least one feedback mechanism to provide haptic guidance, during manipulation of the haptic device, based on a relationship between the representation of the anatomy of the patient and at least one of a position, an orientation, a velocity, and an acceleration of a portion of the haptic device.

101. The method of claim 100, further comprising the step of:

adjusting the representation of the anatomy of the patient in response to movement of the anatomy during the procedure.

102. The method of claim 100, further comprising the step of:

defining a parameter relative to the representation of the anatomy.

103. The method of claim 102, wherein the parameter comprises a distance.

104. The method of claim 102, further comprising the step of:

controlling the haptic device to provide the at least one of haptic guidance based on the parameter and the at least one of a position, an orientation, a velocity, and an acceleration of the portion of the haptic device.

105. The method of claim 100, further comprising the step of:

associating a virtual object with the representation of the anatomy.

106. The method of claim 105, further comprising the step of:

controlling the haptic device to provide the haptic guidance based on the virtual object and the at least one of a position, an orientation, a velocity, and an acceleration of the portion of the haptic device.

107. The method of claim 105, further comprising the steps of:

monitoring a position of the anatomy to detect movement of the anatomy; and

adjusting the virtual object in response to the detected movement.

108. The method of claim 105, wherein the step of controlling the haptic device includes constraining the portion of the haptic device against penetrating at least a portion of the virtual object.

109. The method of claim 105, wherein at least a portion of the virtual object represents a portion of material to be removed from the anatomy.

110. The method of claim 105, wherein a shape of at least a portion of the virtual object substantially corresponds to a shape of a surface of an implant to be fitted to the anatomy.

111. The method of claim 105, further comprising the step of:

superimposing a representation of the virtual object on the representation of the anatomy.

112. The method of claim 105, wherein the virtual object represents a pathway from a first position to a second position.

113. The method of claim 112, wherein second position includes a target region of the anatomy.

114. The method of claim 112, further comprising the steps of:

activating the virtual object so that movement of the portion of the haptic device is constrained along the pathway; and

deactivating the virtual object when the portion of the haptic device reaches the second position.

115. The method of claim 114, further comprising the step of:

deactivating the virtual object to enable the portion of the haptic device to deviate from the pathway.

116. The method of claim 100, wherein the haptic device includes an arm, a surgical tool coupled to the arm, and an interface associated with at least one of the arm and the surgical tool.

117. The method of claim 116, wherein the haptic device includes a first part configured to enable a user to change a configuration of the arm and a second part configured to enable the user to move the surgical tool relative to the arm.

118. The method of claim 116, further comprising the step of:

manipulating the interface to simultaneously change a configuration of the arm and move the surgical tool relative to the arm.

119. The method of claim 100, where the feedback supplied by the feedback mechanism includes at least one of a force, a torque, and vibration.

120. The method of claim 100, wherein the feedback supplied by the feedback mechanism opposes a user's manipulation of the haptic device.

121. The method of claim 120, wherein the feedback is determined based on a proximity of the portion of the haptic device to a virtual boundary associated with the representation of the anatomy.

122. The method of claim 120, wherein a magnitude of the feedback increases as the portion of the haptic device approaches a virtual boundary associated with the representation of the anatomy.

123. The method of claim 100, wherein the haptic guidance communicates information to a user manipulating the surgical device about a position of the portion of the surgical device relative to at least one of a virtual boundary associated with the representation of the anatomy, a parameter relative to the representation of the anatomy, and the anatomy.

124. The method of claim 100, further comprising the step of:

offsetting a force feedback curve for controlling the haptic device by a desired value.

125. The method of claim 124, further comprising the steps of:

storing the desired value; and

associating the desired value with a user.

126. The method of claim 124, wherein the step of offsetting the force feedback curve includes increasing or decreasing a size of a haptic object.

127. The method of claim 124, wherein the step of offsetting the force feedback curve includes increasing or decreasing a size of a representation of a surgical tool coupled to the haptic device.

128. The method of claim 100, further comprising the steps of:

monitoring a position of the haptic device.

129. The method of claim 100, further comprising the steps of:

creating a representation of a surgical tool coupled to the haptic device.

130. The method of claim 129, further comprising the steps of:

updating the representation of the surgical tool as a user manipulates the haptic device to perform the procedure on the patient.

131. The method of claim 129, wherein the representation of the surgical tool includes a representation of at least one of a tip of the surgical tool and a shaft of the surgical tool.

132. The method of claim 129, further comprising the step of:

indicating an allowable angle of inclination of a shaft of the surgical tool.

133. The method of claim 100, further comprising the steps of:

creating a representation of at least a portion of material to be removed from the anatomy;

manipulating the haptic device to remove material from the anatomy; and

creating a representation of the material removed by the surgical device.

134. The method of claim 133, further comprising the steps of:

creating the representation of the portion of material to be removed in a first color;

creating the representation of the material removed by the haptic device in a second color when a desired amount of material has been removed; and

creating the representation of the material removed by the haptic device in a third color when the material removed by the haptic device exceeds the desired amount of material.

135. The method of claim 100, further comprising the step of:

generating at least one display configured to guide a user manipulating the haptic device through the procedure.

136. The method of claim 135, wherein the at least one display prompts the user to perform a task.

137. A method for joint replacement, comprising the steps of:

creating a representation of a first bone;

creating a representation of a second bone;

planning bone preparation for implanting a first implant on the first bone;

preparing the first bone to receive the first implant by manipulating a surgical tool to sculpt the first bone;

planning bone preparation for implanting a second implant on the second bone after preparing the first bone; and

preparing the second bone to receive the second implant by manipulating the surgical tool to sculpt the second bone.

138. The method of claim 137, further comprising the steps of:

designating landmarks on the representation of the first bone; and

designating landmarks on the representation of the second bone.

139. The method of claim 138, wherein the landmarks on the representation of the first bone include at least one of a medial malleolus, a lateral malleolus, a rotational landmark, a knee center, a hip center, a medial epicondyle, and a lateral epicondyle.

140. The method of claim 138, wherein the landmarks on the representation of the second bone include at least one of a medial malleolus, a lateral malleolus, a rotational landmark, a knee center, a hip center, a medial epicondyle, and a lateral epicondyle.

141. The method of claim 137, wherein the step of planning bone preparation for implanting the first implant includes superimposing a representation of the first implant on the representation of the first bone.

142. The method of claim 137, wherein the step of planning bone preparation for implanting the second implant includes superimposing a representation of the second implant on the representation of the second bone.

143. The method of claim 137, wherein the step of planning bone preparation for implanting the first implant includes associating a representation of the first implant with the representation of the first bone.

144. The method of claim 137, wherein the step of planning bone preparation for implanting the second implant includes associating a representation of the second implant with the representation of the second bone.

145. The method of claim 137, wherein the step of planning bone preparation for implanting the first implant includes adjusting at least one of a depth, a rotation, a medial/lateral position, an anterior/posterior position, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the first implant.

146. The method of claim 137, wherein the step of planning bone preparation for implanting the second implant includes adjusting at least one of a depth, a rotation, a medial/lateral position, an anterior/posterior position, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the second implant.

147. The method of claim 137, further comprising the step of:

displaying at least one of a depth, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the first implant on a display device.

148. The method of claim 137, further comprising the step of:

displaying at least one of a depth, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the second implant on a display device.

149. The method of claim 137, wherein the step of planning bone preparation for implanting the first implant includes associating a representation of the first implant with the representation of the first bone based at least in part on a detected location of cartilage in a region of the first bone.

150. The method of claim 137, further comprising the step of:

adjusting the representation of the first bone in response to movement of the first bone.

151. The method of claim 137, further comprising the step of:

adjusting the representation of the second bone in response to movement of the second bone.

152. The method of claim 137, wherein the step of planning bone preparation for implanting the first implant includes detecting a height of a cartilage surface above the first bone.

153. The method of claim 152, wherein the step of planning bone preparation for implanting the first implant includes aligning at least a portion of a representation of the first implant with a representation of the height of the cartilage surface.

154. The method of claim 137, further comprising the step of:

fitting the first implant to the first bone.

155. The method of claim 154, wherein the step of planning bone preparation for implanting the second implant includes associating a representation of the second implant with the representation of the second bone based at least in part on a detected location of the first implant on the first bone.

156. The method of claim 154, further comprising the steps of:

moving a joint to a first position;

identifying a first point corresponding to a first location in the joint, when the joint is in the first position;

moving the joint to a second position;

identifying a second point corresponding to a second location in the joint, when the joint is in the second position;

planning bone preparation for implanting the second implant on the second bone based at least in part on the first and second points.

157. The method of claim 156, wherein the step of moving the joint to the first position includes moving the joint into one of flexion and extension.

158. The method of claim 156, wherein the step of moving the joint to the second position includes moving the joint into one of flexion and extension.

159. The method of claim 156, wherein at least one of the first location and the second location includes a location on the first implant fitted to the first bone.

160. The method of claim 156, wherein at least one of the first location and the second location includes a location on a pre-existing implant disposed in the joint.

161. The method of claim 156, wherein the step of planning bone preparation for implanting the second implant includes aligning a centerline of a representation of the second implant with the first and second points.

162. The method of claim 137, wherein the step of preparing the first bone includes constraining the surgical tool against at least one of penetrating a virtual boundary associated with the representation of the first bone and exceeding a parameter defined with respect to the representation of the first bone.

163. The method of claim 137, wherein the step of preparing the second bone includes constraining the surgical tool against at least one of penetrating a virtual boundary associated with the representation of the second bone and exceeding a parameter defined with respect to the representation of the second bone.

164. The method of claim 137, further comprising the steps of:

sculpting the first bone with a surgical tool; and

constraining the surgical tool so that a tip of the surgical tool is constrained against penetrating a virtual boundary.

165. The method of claim 164, wherein at least a portion of the virtual boundary comprises a representation of the first implant.

166. The method of claim 164, wherein a shape of at least a portion of the virtual boundary corresponds to a shape of a surface of the first implant.

167. The method of claim 164, further comprising the steps of:

adjusting the virtual boundary in response to movement of the first bone.

168. The method of claim 137, further comprising the steps of:

sculpting the second bone with a surgical tool; and

constraining the surgical tool so that a tip of the surgical tool is constrained against penetrating a virtual boundary.

169. The method of claim 168, wherein at least a portion of the virtual boundary comprises a representation of the second implant.

170. The method of claim 168, wherein a shape of at least a portion of the virtual boundary corresponds to a shape of a surface of the second implant.

171. The method of claim 168, further comprising the steps of:

adjusting the virtual boundary in response to movement of the second bone.

172. The method of claim 137, wherein the step of preparing the first bone includes the steps of:

superimposing a representation of a portion of material to be removed from the first bone on the representation of the first bone; and

updating the representation of the portion of material to be removed from the first bone with a representation of a portion of material actually removed by the surgical tool.

173. The method of claim 172, wherein the portion of material to be removed corresponds to at least a portion of a virtual object associated with the representation of the first bone.

174. The method of claim 137, wherein the step of preparing the second bone includes the steps of:

superimposing a representation of a portion of material to be removed from the second bone on the representation of the second bone; and

updating the representation of the portion of material to be removed from the second bone with a representation of a portion of material actually removed by the surgical tool.

175. The method of claim 174, wherein the portion of material to be removed corresponds to at least a portion of a virtual object associated with the representation of the second bone.

176. The method of claim 137, further comprising the steps of:

creating a representation of the surgical tool; and

updating the representation of the surgical tool and at least one of the representation of the first and the representation of the second bone as the surgical tool and at least one of the first bone and the second bone move.

177. The method of claim 137, further comprising the steps of:

placing at least one of the first bone and the second bone in a support device; and

actuating the support device to move at least one of the first bone and the second bone from a first position to a second position.

178. The method of claim 177, wherein the step of actuating the support device includes the steps of:

determining an actual pose of at least one of the first bone and the second bone;

determining a desired pose of the at least one of the first bone and the second bone; and

actuating the support device to move the at least one of the first bone and the second bone from the actual pose to the desired pose.

179. A surgical planning method, comprising the steps of:

detecting a height of a cartilage surface above a bone;

creating a representation of the bone and a representation of the height of the cartilage surface; and

planning bone preparation for implanting an implant on the bone based at least in part on the detected height of the cartilage surface.

180. The method of claim 179, wherein the step of planning bone preparation includes aligning at least a portion of a representation of the implant with the representation of the height of the cartilage surface.

181. The method of claim 179, wherein the step of planning bone preparation includes adjusting at least one of a depth, a rotation, a medial/lateral position, an anterior/posterior position, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the implant.

182. The method of claim 179, further comprising the step of:

displaying at least one of a depth, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the implant on a display device.

183. The method of claim 180, wherein the representation of the height of the cartilage surface includes at least one of a visual representation and a numerical representation.

184. The method of claim 180, further comprising the step of:

superimposing a representation of the implant on the representation of the bone.

185. The method of claim 179, further comprising the step of:

associating a representation of an implant with the representation of the bone.

186. The method of claim 179, further comprising the steps of:

sculpting the bone with a surgical tool; and

constraining the surgical tool so that a tip of the surgical tool is constrained against penetrating a virtual boundary.

187. The method of claim 186, wherein at least a portion of the virtual boundary comprises a representation of the implant.

188. The method of claim 186, wherein a shape of at least a portion of the virtual boundary corresponds to a shape of a surface of the implant.

189. The method of claim 179, further comprising the steps of:

sculpting the bone to receive the implant; and

fitting the implant to the bone.

190. The method of claim 189, further comprising the steps of:

creating a representation of a second bone of the joint;

moving the joint to a first position;

identifying a first point corresponding to a first location in the joint, when the joint is in the first position;

moving the joint to a second position;

identifying a second point corresponding to a second location in the joint, when the joint is in the second position;

planning bone preparation for implanting a second implant on the second bone based at least in part on the first and second points.

191. The method of claim 190, wherein the step of moving the joint to the first position includes moving the joint into one of flexion and extension.

192. The method of claim 190, wherein the step of moving the joint to the second position includes moving the joint into one of flexion and extension.

193. The method of claim 190, wherein at least one of the first location and the second location includes a location on the implant fitted to the bone.

194. The method of claim 190, wherein at least one of the first location and the second location includes a location on a pre-existing implant disposed in the joint.

195. The method of claim 190, wherein the step of planning bone preparation for implanting the second implant includes aligning a centerline of a representation of the second implant with the first and second points.

196. The method of claim 190, wherein the step of planning bone preparation for implanting the second implant includes adjusting at least one of a depth, a rotation, a medial/lateral position, an anterior/posterior position, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the second implant.

197. The method of claim 190, further comprising the step of:

superimposing a representation of the second implant on the representation of the second bone.

198. The method of claim 190, further comprising the step of:

displaying at least one of a depth, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the second implant on a display device.

199. The method of claim 190, further comprising the step of:

associating a representation of the second implant with the representation of the second bone.

200. The method of claim 190, further comprising the steps of:

sculpting the second bone with a surgical tool; and

constraining the surgical tool so that a tip of the surgical tool is constrained against penetrating a virtual boundary.

201. The method of claim 200, wherein at least a portion of the virtual boundary comprises a representation of the second implant.

202. The method of claim 200, wherein a shape of at least a portion of the virtual boundary corresponds to a shape of a surface of the second implant.

203. The method of claim 200, further comprising the steps of:

adjusting the virtual boundary in response to movement of the second bone.

204. A surgical planning method, comprising the steps of:

creating a representation of a bone of a joint;

moving the joint to a first position;

identifying a first point corresponding to a first location in the joint, when the joint is in the first position;

moving the joint to a second position;

identifying a second point corresponding to a second location in the joint, when the joint is in the second position; and

planning bone preparation for implanting an implant on the bone based at least in part on the first and second points.

205. The method of claim 204, wherein the step of moving the joint to the first position includes moving the joint into one of flexion and extension.

206. The method of claim 204, wherein the step of moving the joint to the second position includes moving the joint into one of flexion and extension.

207. The method of claim 204, wherein at least one of the first location and the second location includes a location on an implant disposed on an opposite bone of the joint.

208. The method of claim 204, wherein at least one of the first location and the second location includes a location on a second implant disposed in the joint.

209. The method of claim 204, wherein the step of planning bone preparation includes aligning a centerline of a representation of the implant with the first and second points.

210. The method of claim 204, wherein the step of planning bone preparation includes adjusting at least one of a depth, a rotation, a medial/lateral position, an anterior/posterior position, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the implant.

211. The method of claim 204, further comprising the step of:

superimposing a representation of the implant on the representation of the bone.

212. The method of claim 204, further comprising the step of:

displaying at least one of a depth, an internal/external angle, a varus/valgus angle, a flexion angle, and a size of a representation of the implant on a display device.

213. The method of claim 204, further comprising the step of:

associating a representation of the implant with the representation of the bone.

214. The method of claim 204, further comprising the steps of:

sculpting the bone with a surgical tool; and

constraining the surgical tool so that a tip of the surgical tool is constrained against penetrating a virtual boundary.

215. The method of claim 214, wherein at lease a portion of the virtual boundary comprises a representation of the implant.

216. The method of claim 214, wherein a shape of at least a portion of the virtual boundary corresponds to a shape of a surface of the implant.

217. The method of claim 214, further comprising the steps of:

adjusting the virtual boundary in response to movement of the bone.

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