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(54) **SYSTEMS AND METHODS FOR HAPTIC CONTROL OF A SURGICAL TOOL**

(71) Applicant: **MAKO Surgical Corp.**, Fort Lauderdale, FL (US)

(72) Inventors: **Jason Otto**, Plantation, FL (US); **Radu Iorgulescu**, Fort Lauderdale, FL (US); **Chris Lightcap**, Davie, FL (US); **Brian Schmitz**, Fort Lauderdale, FL (US); **Jason Wojcik**, Weston, FL (US); **Carinne Cecile Granchi**, Weston, FL (US)

(73) Assignee: **MAKO Surgical Corp.**, Fort Lauderdale, FL (US)

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A61B 17/16	(2006.01)
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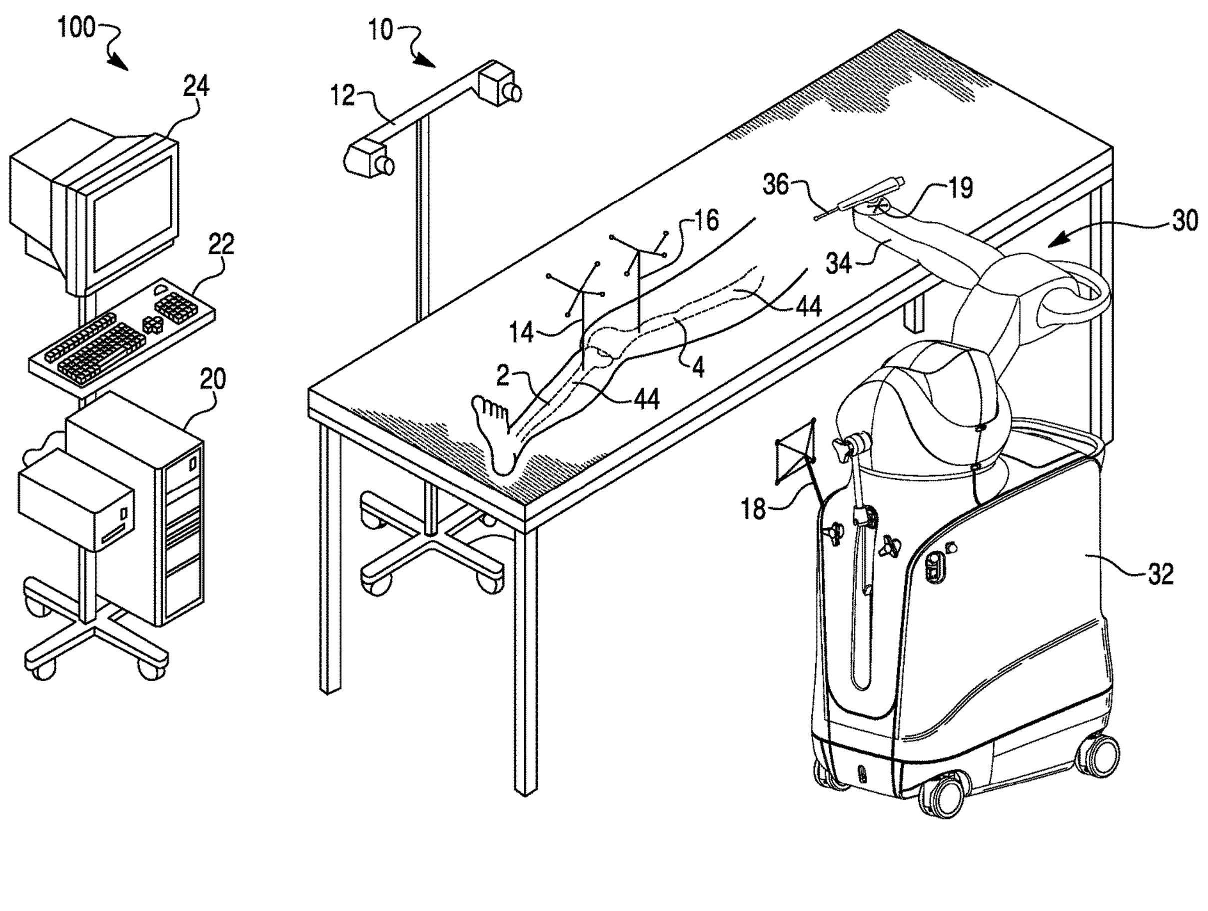
(52) **U.S. Cl.**

CPC ***A61B 17/15*** (2013.01); ***A61B 34/76*** (2016.02); ***A61B 34/30*** (2016.02); *A61B 2034/105* (2016.02); ***A61B 17/142*** (2016.11); ***A61B 17/1615*** (2013.01); ***A61B 17/1703*** (2013.01); ***A61B 34/20*** (2016.02)

(57) **ABSTRACT**

A surgical system includes a surgical tool and a processing circuit. The processing circuit is configured to provide a plurality of virtual haptic interaction points where each virtual haptic interaction point is associated with a portion of the surgical tool such that movement of the surgical tool corresponds to movement of the plurality of virtual haptic interaction points, establish a haptic object that defines a working boundary for the surgical tool, and constrain at least one of the portions of the surgical tool based on a relationship between at least one of the plurality of virtual haptic interaction points and the haptic object.



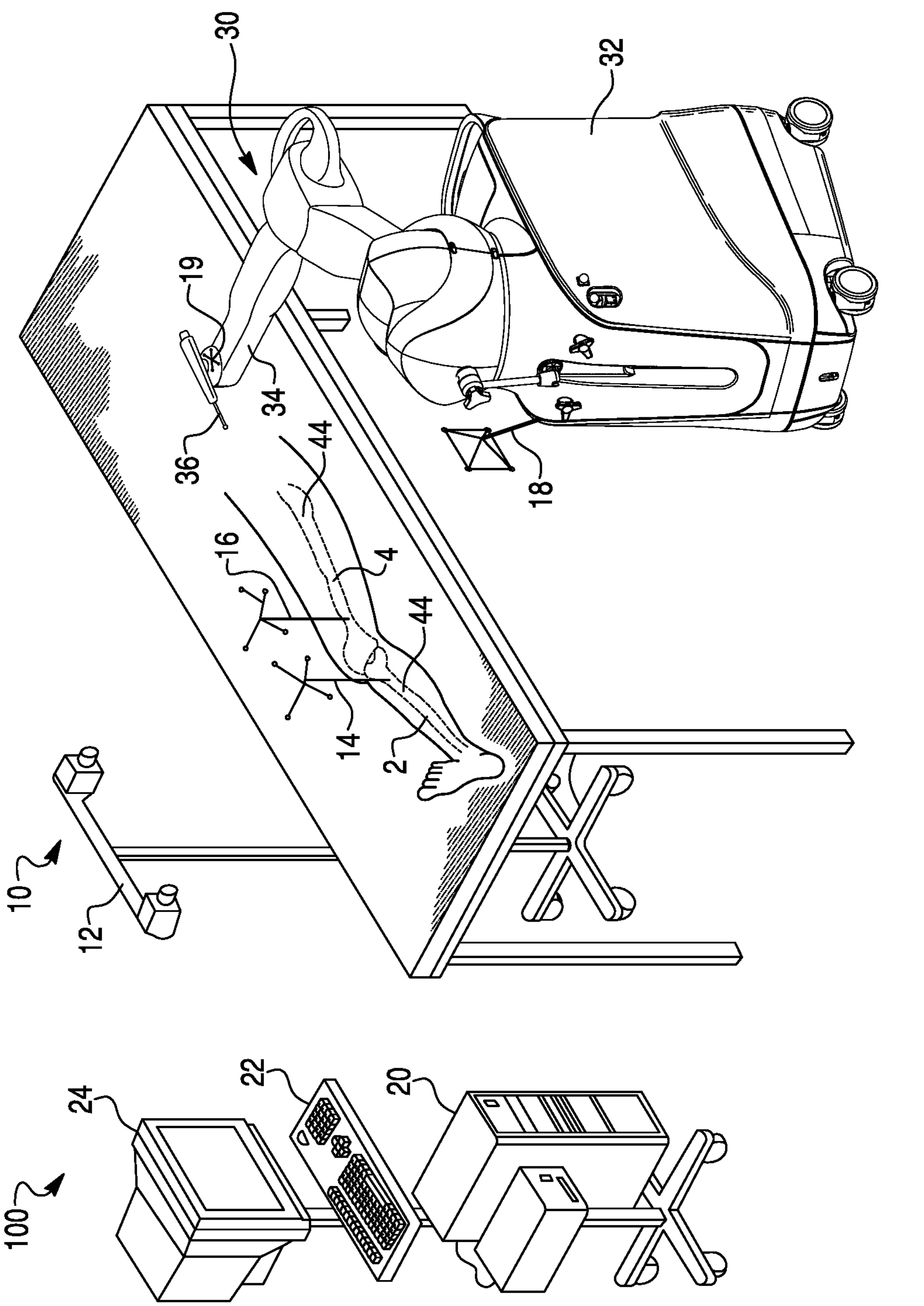


Fig. 1

Fig. 2A

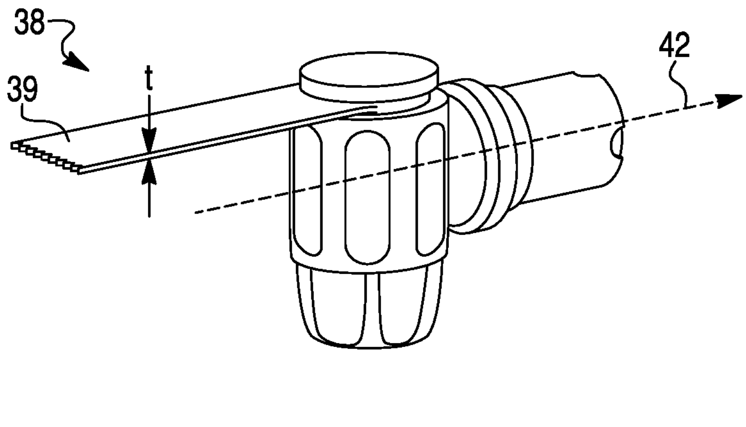


Fig. 2B

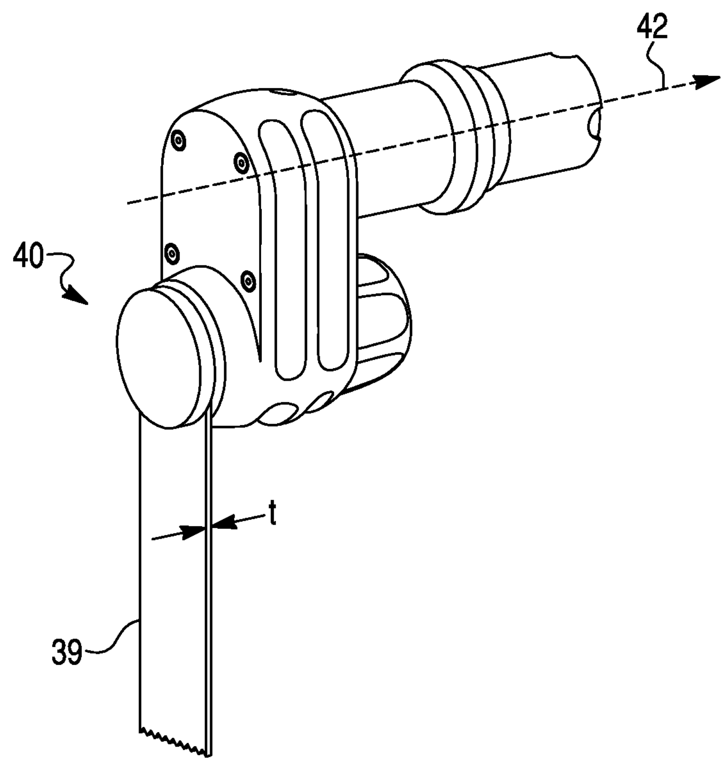


Fig. 3A

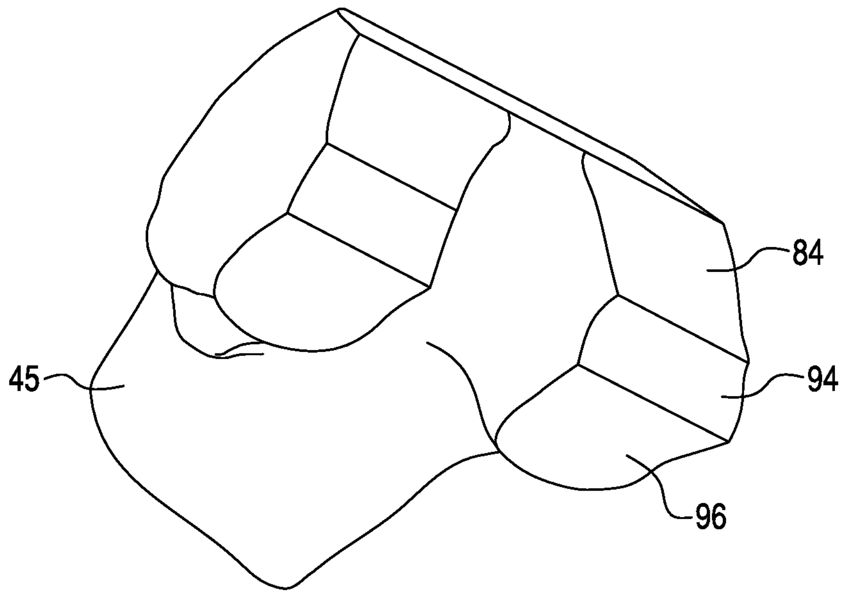


Fig. 3B

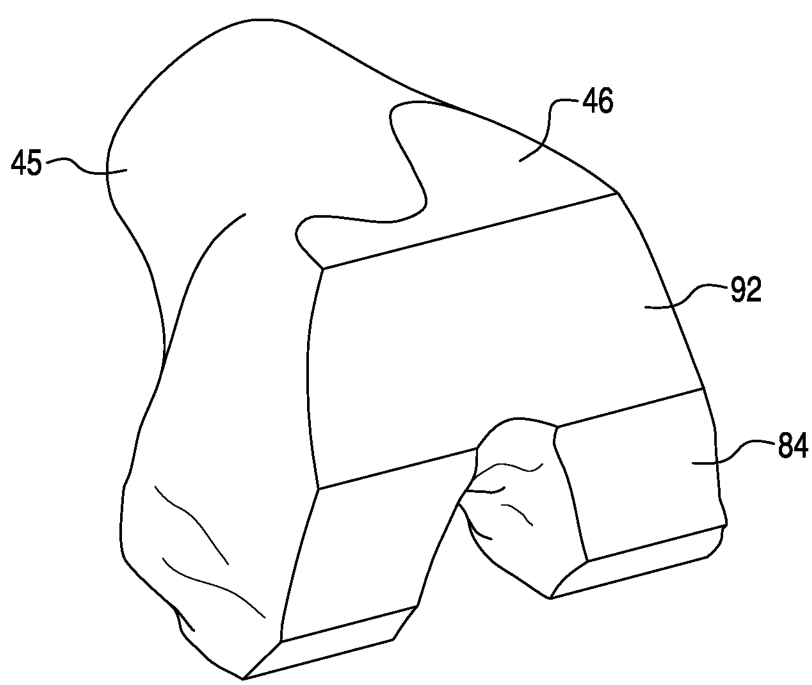


Fig. 3C

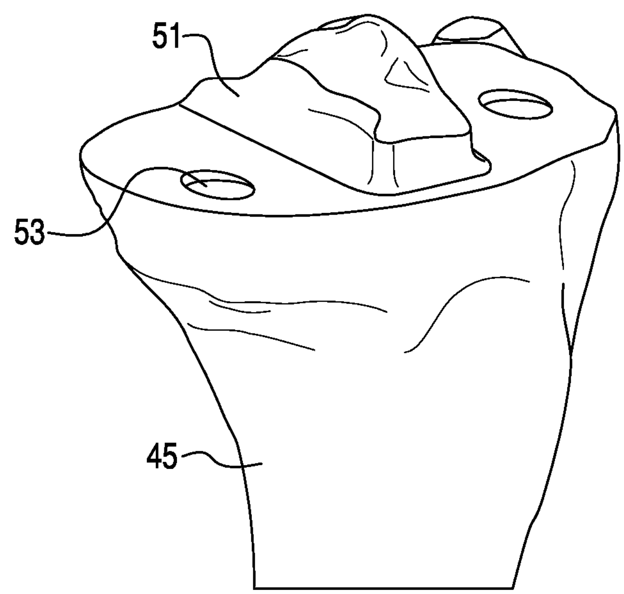


Fig. 3D

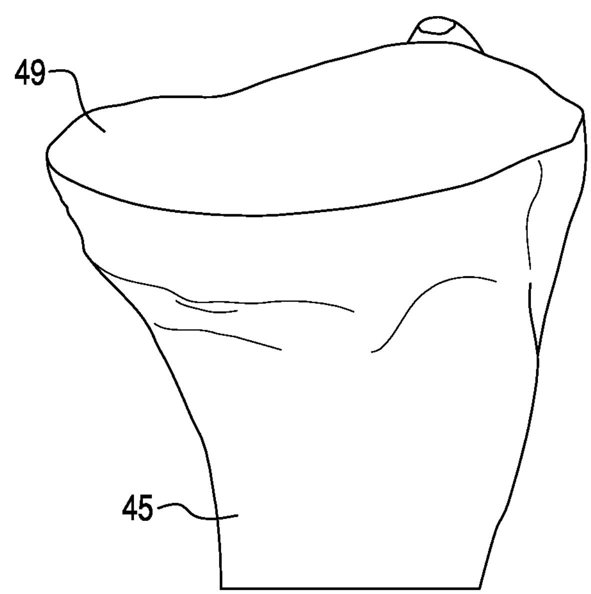


Fig. 4

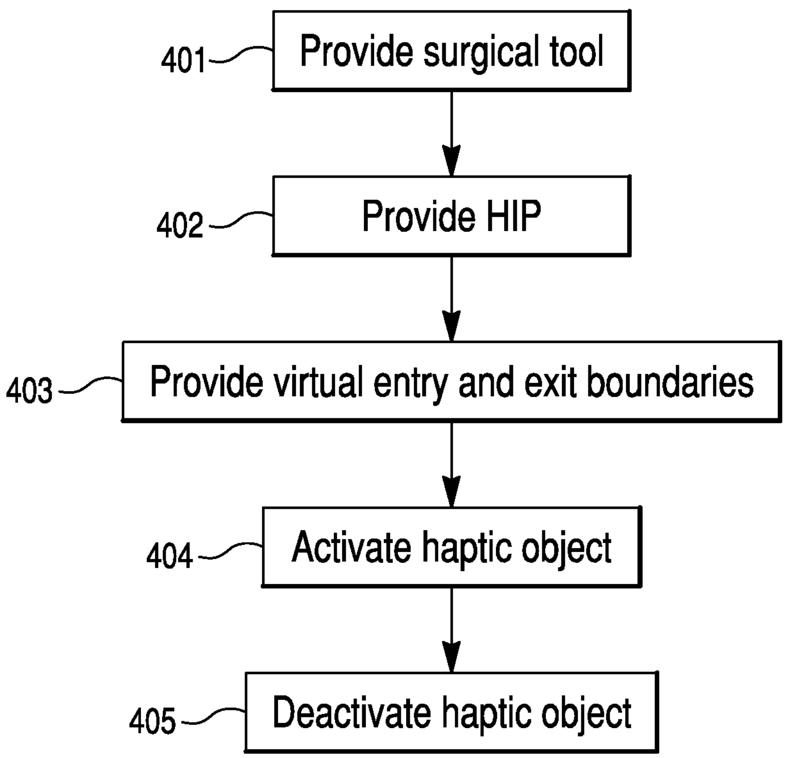

401
Provide surgical tool
402
Provide HIP
403
Provide virtual entry and exit boundaries
404
Activate haptic object
405
Deactivate haptic object

Fig. 5A

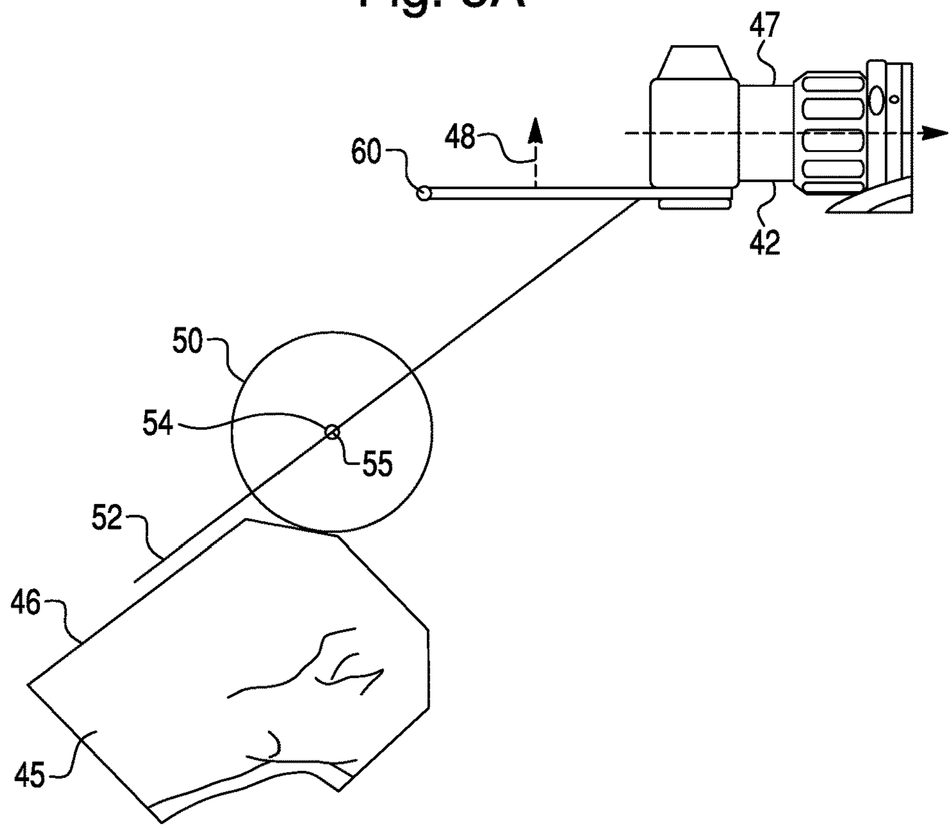


Fig. 5B

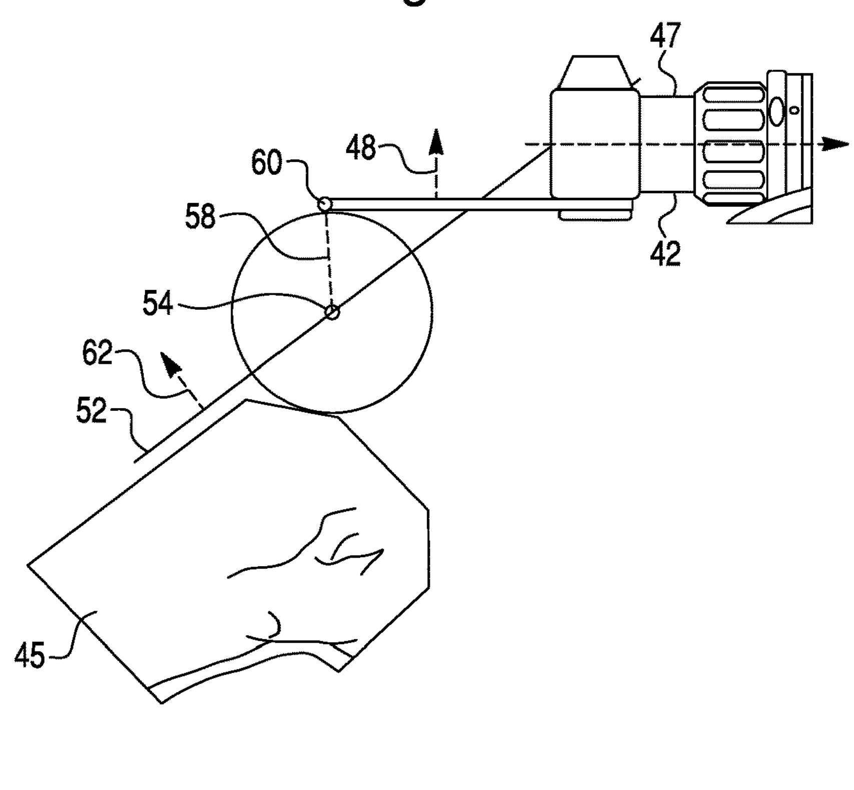


Fig. 5C

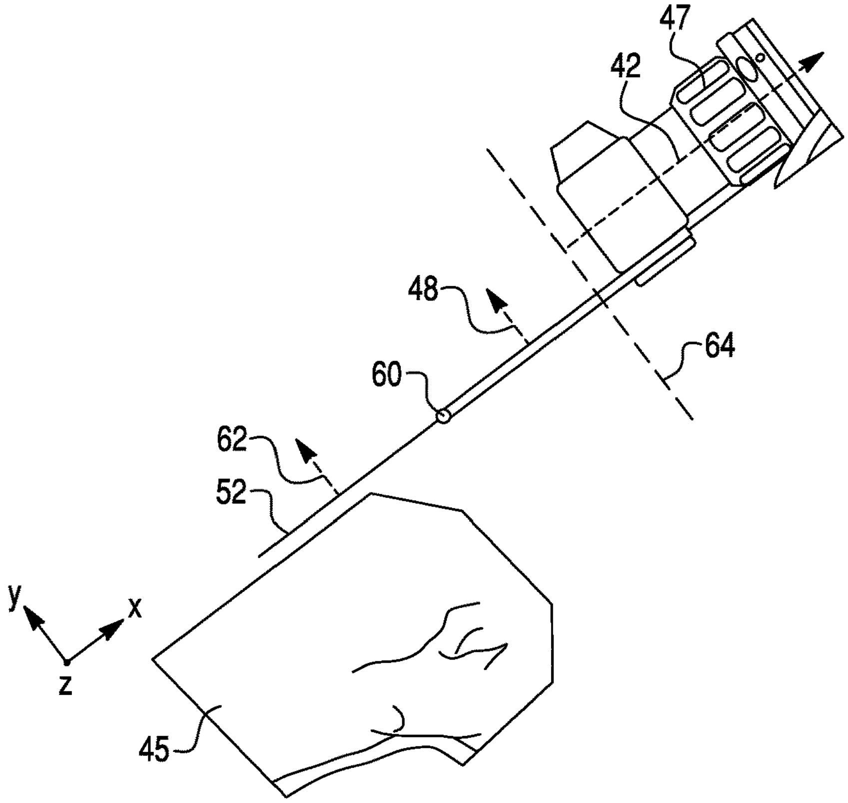


Fig. 5D

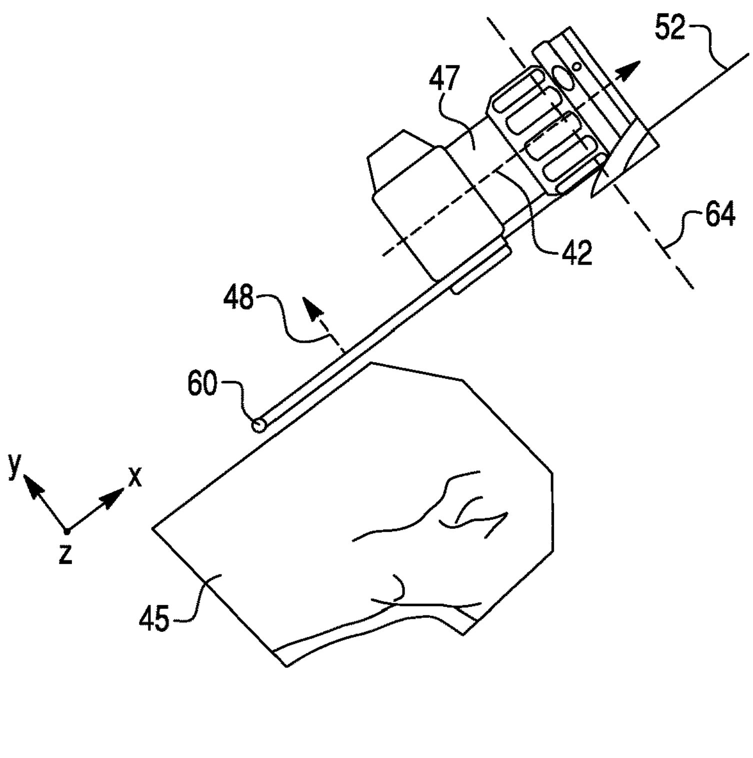


Fig. 5E

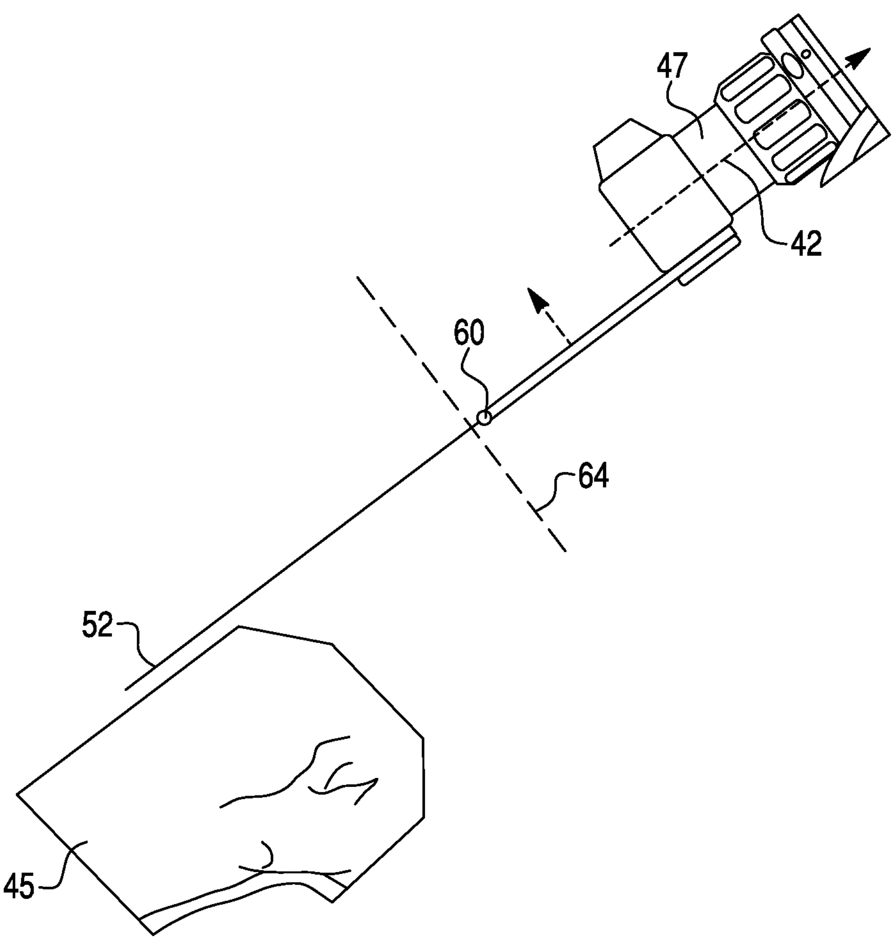


Fig. 6A

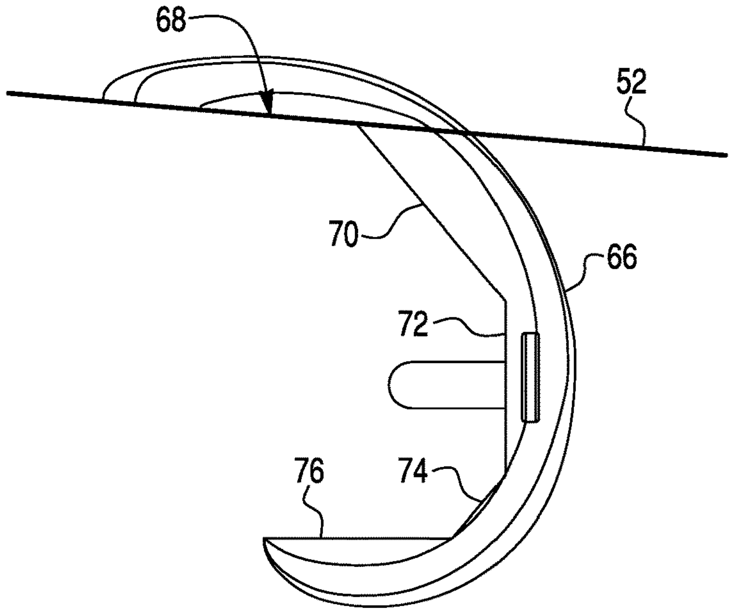


Fig. 6B

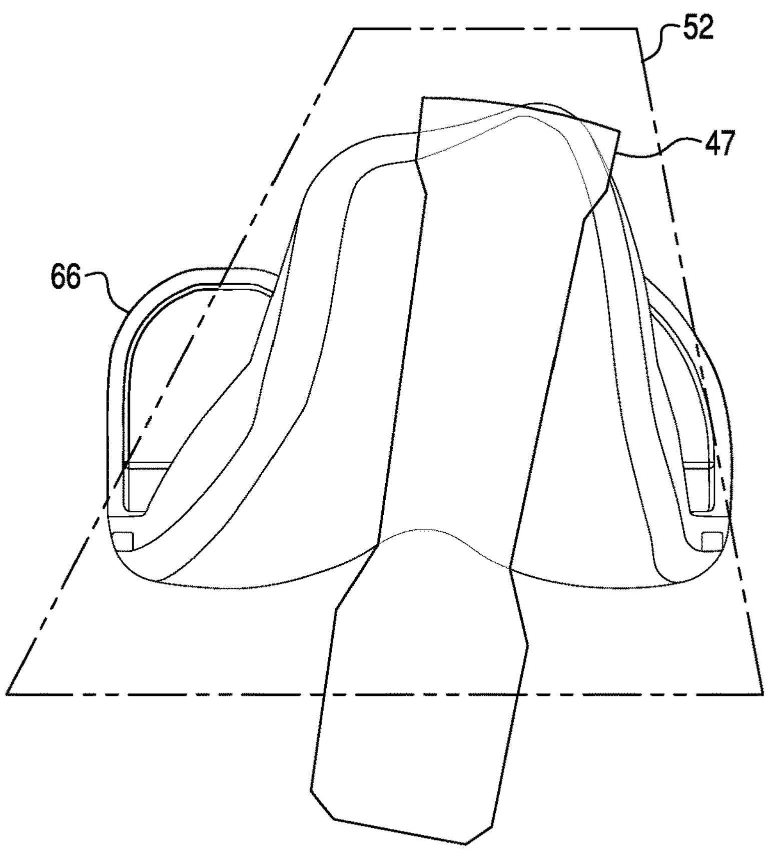


Fig. 7A

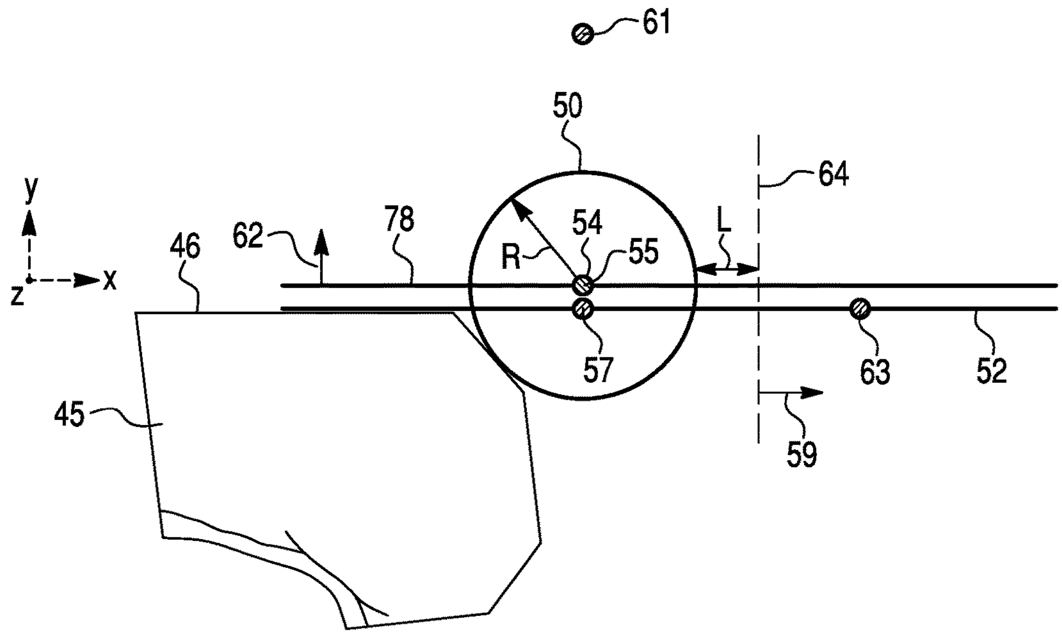

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Fig. 7B

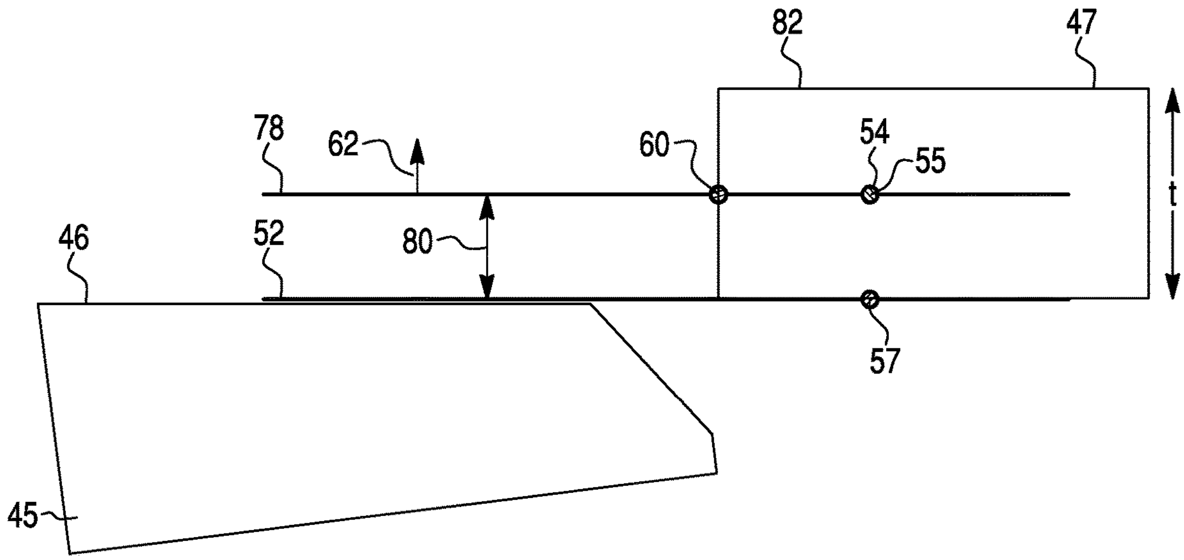
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Fig. 8A

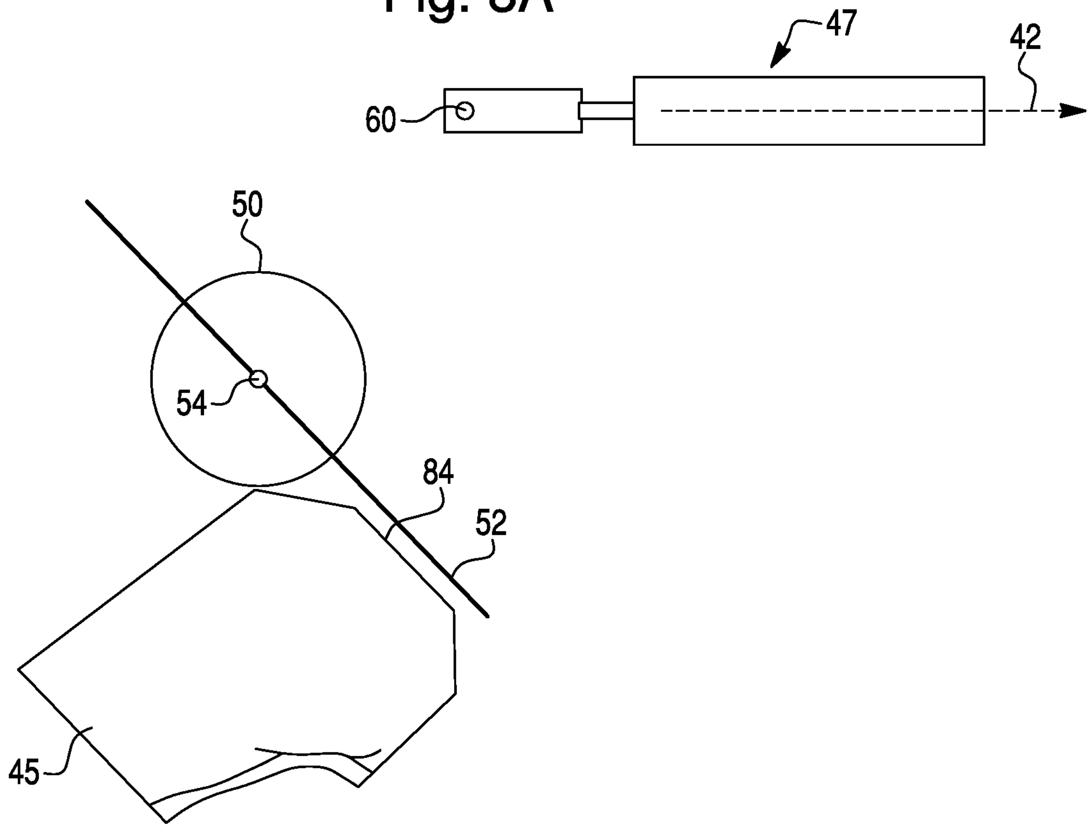
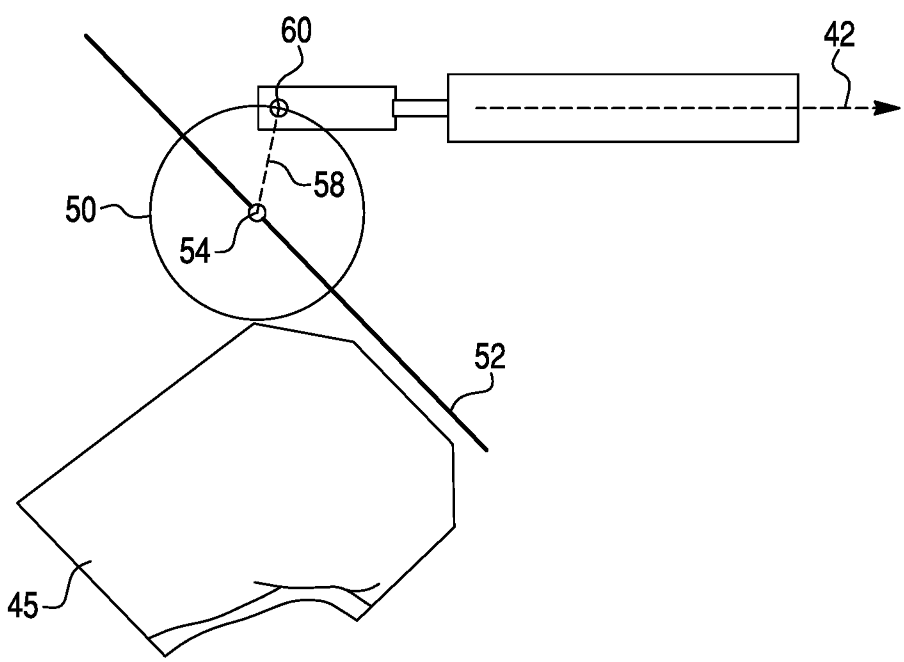


Fig. 8B



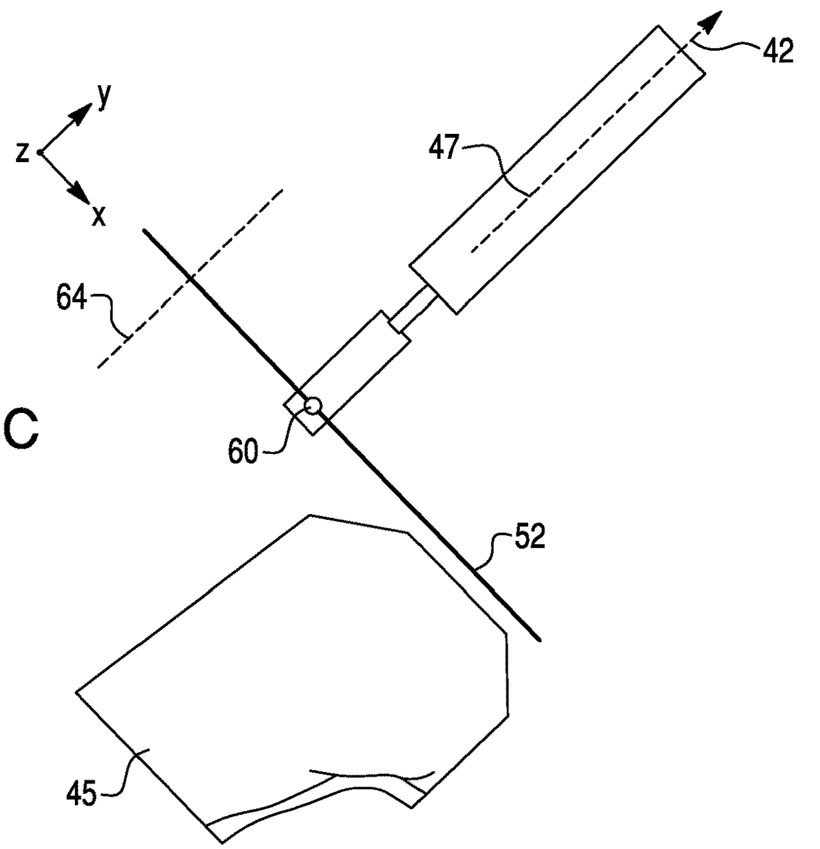


Fig. 8C

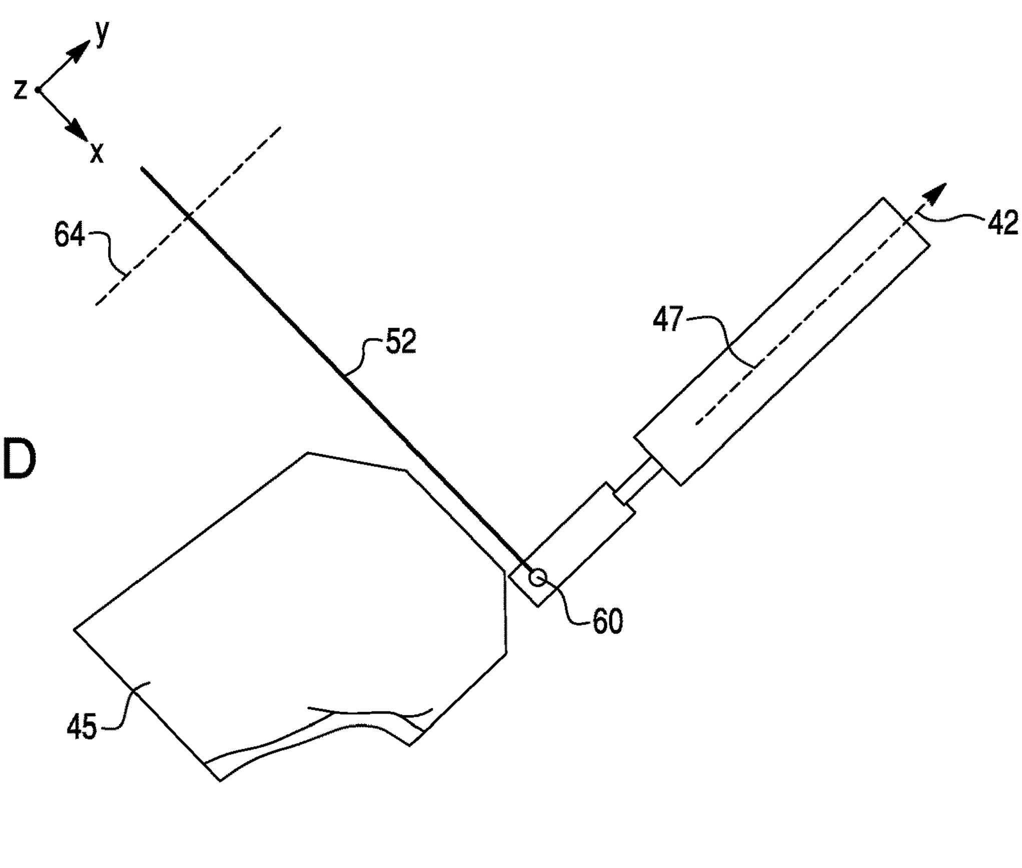


Fig. 8D

Fig. 8E

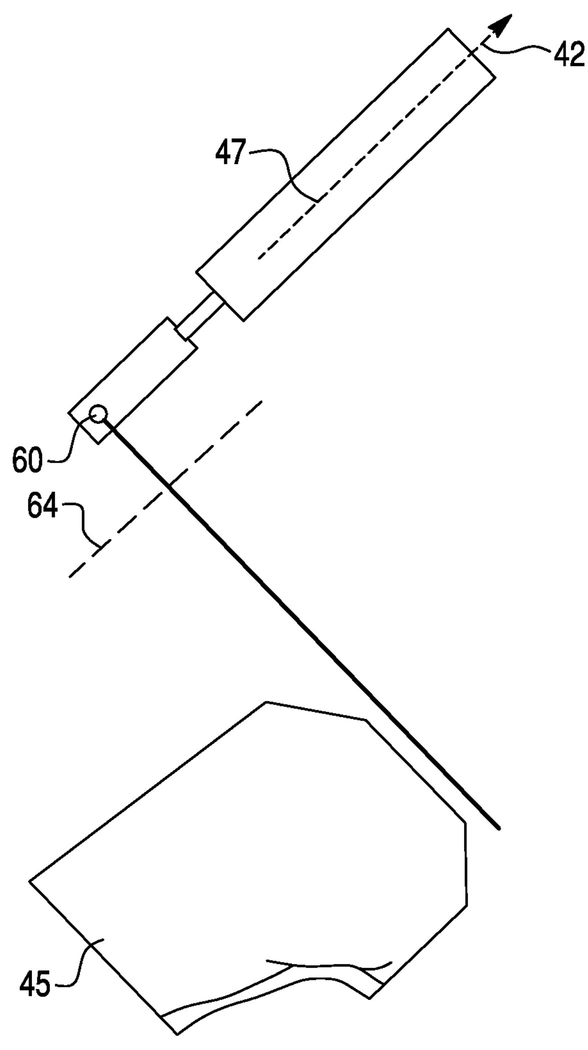


Fig. 9A

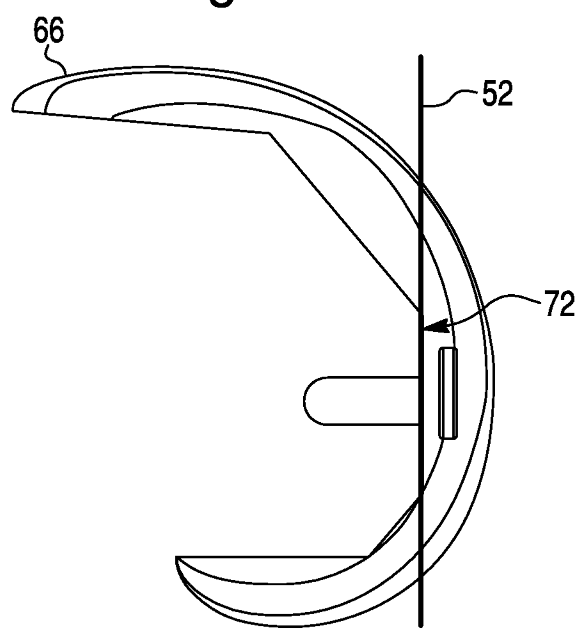


Fig. 9B

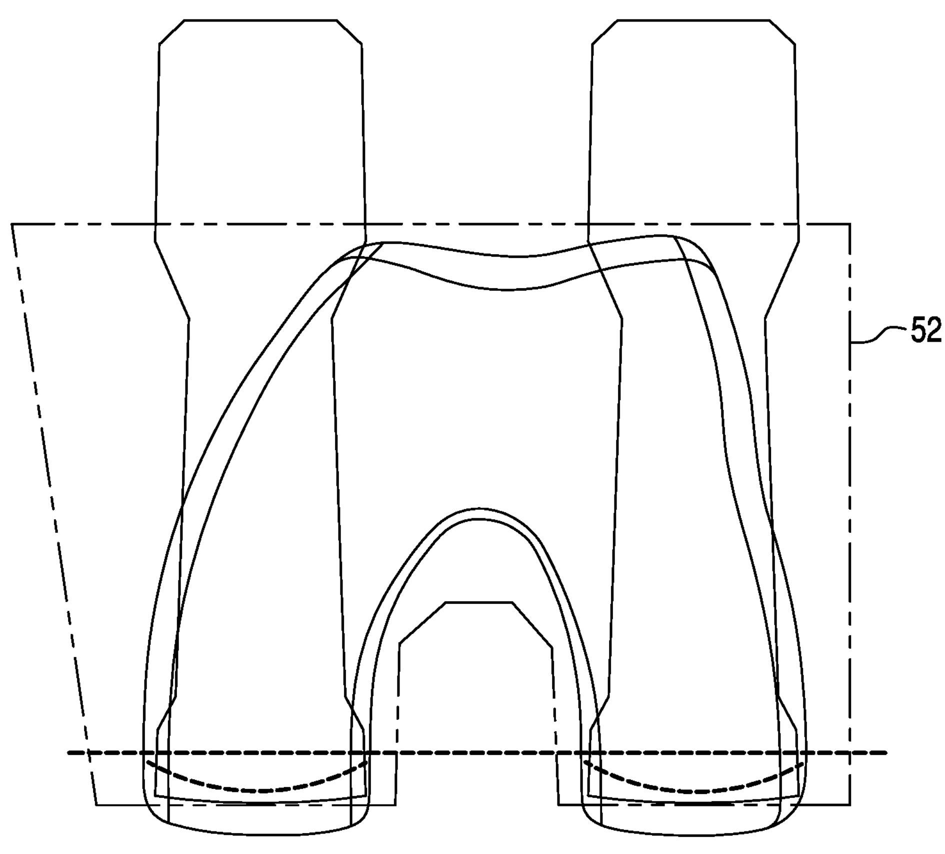
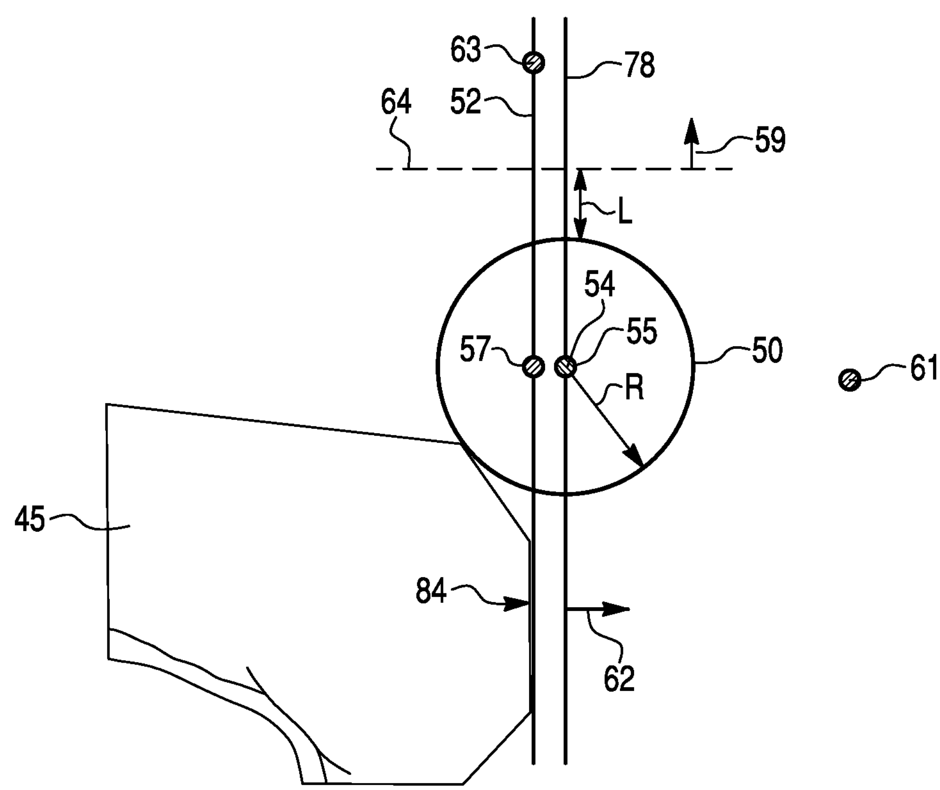


Fig. 10



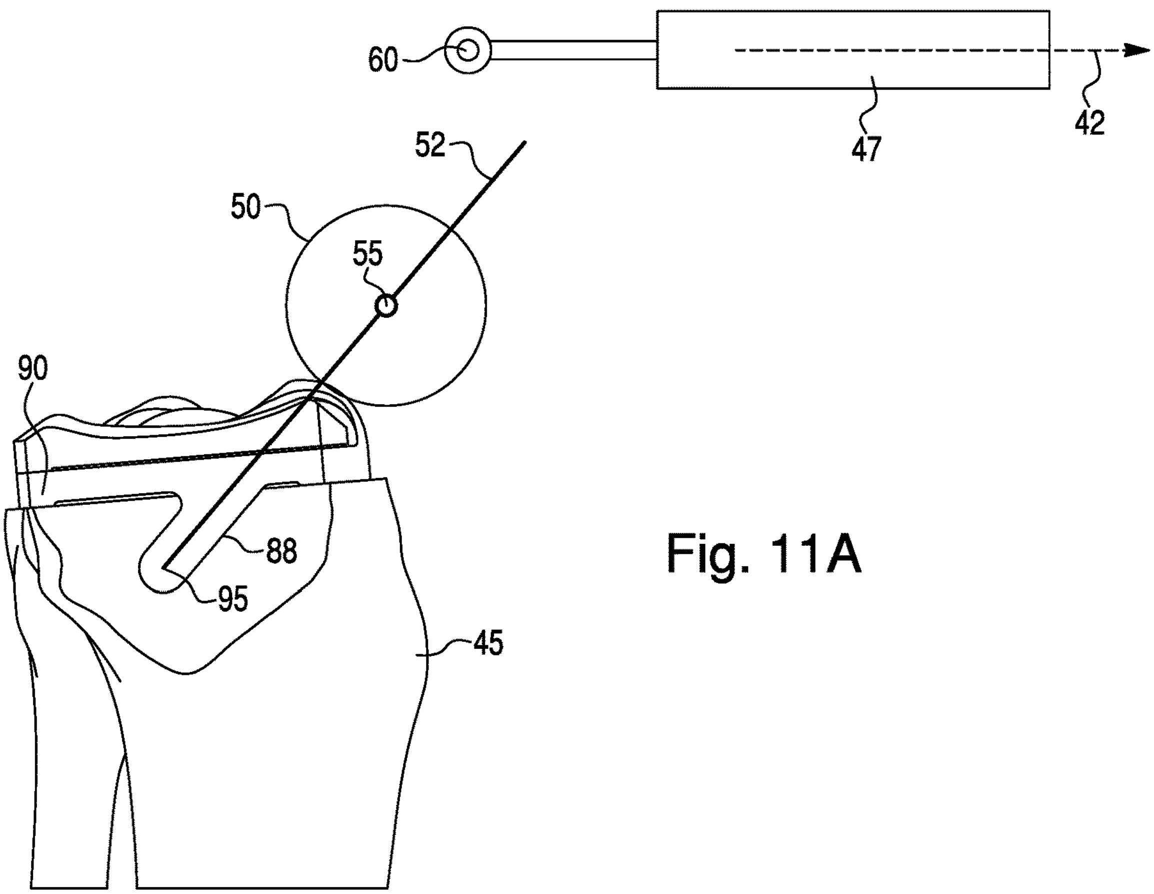


Fig. 11A

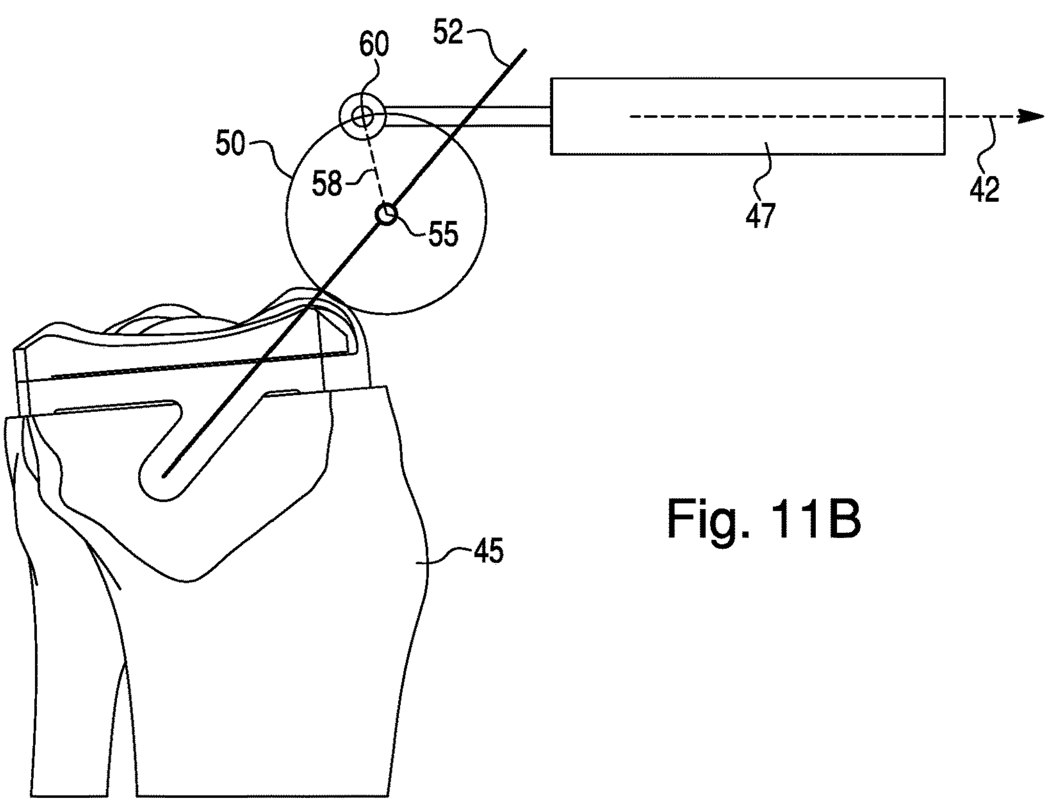


Fig. 11B

Fig. 11C

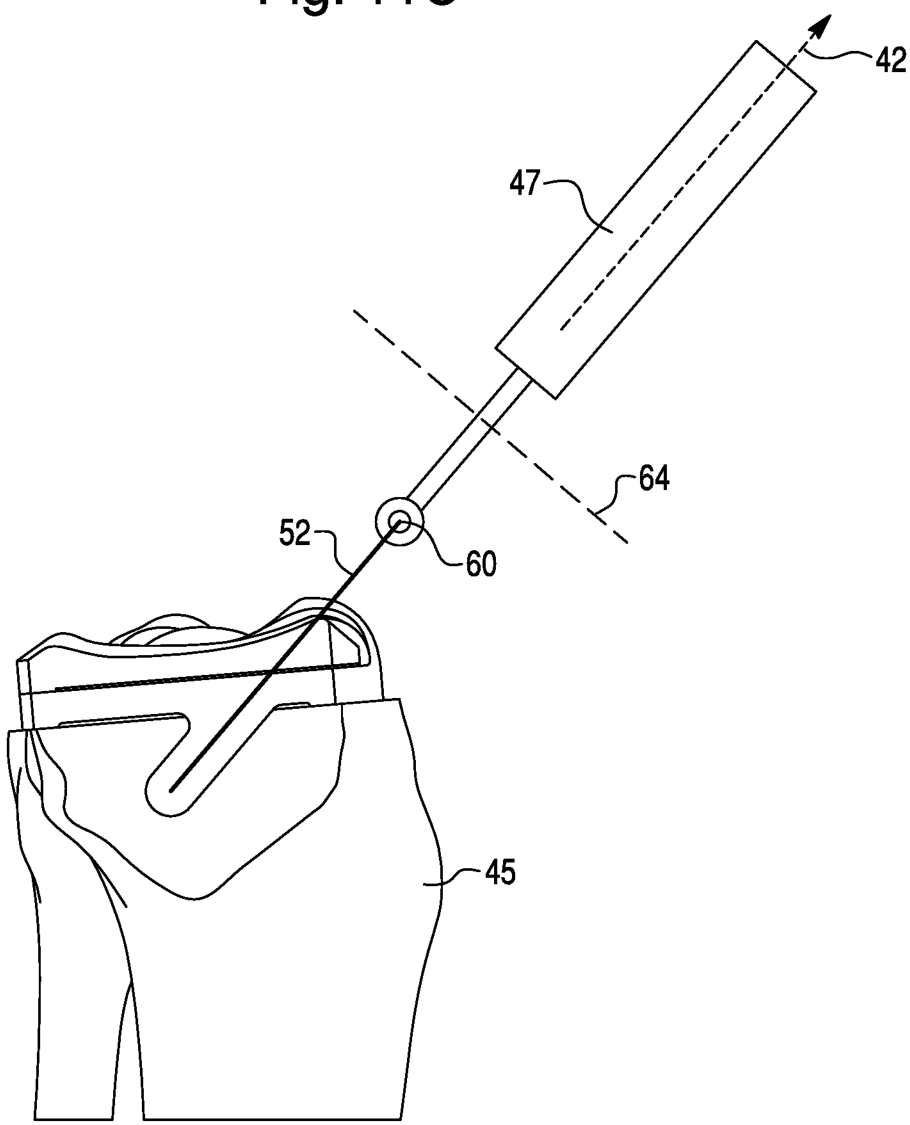


Fig. 11D

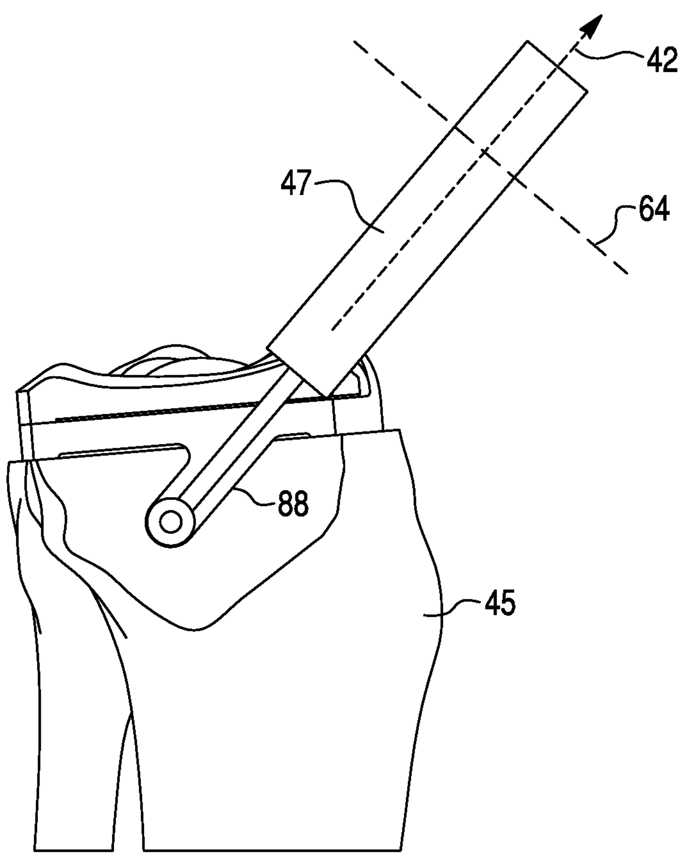


Fig. 11E

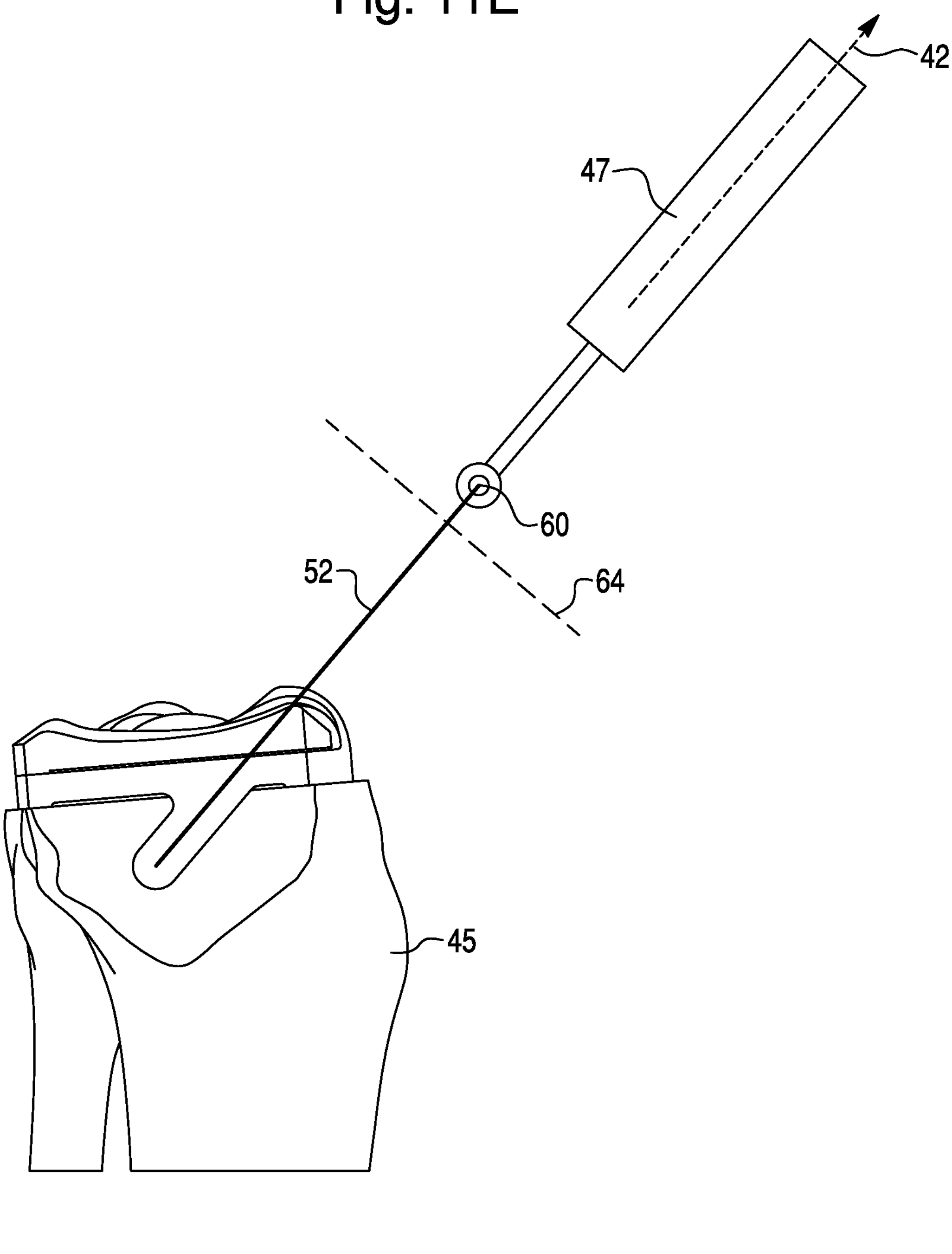


Fig. 12

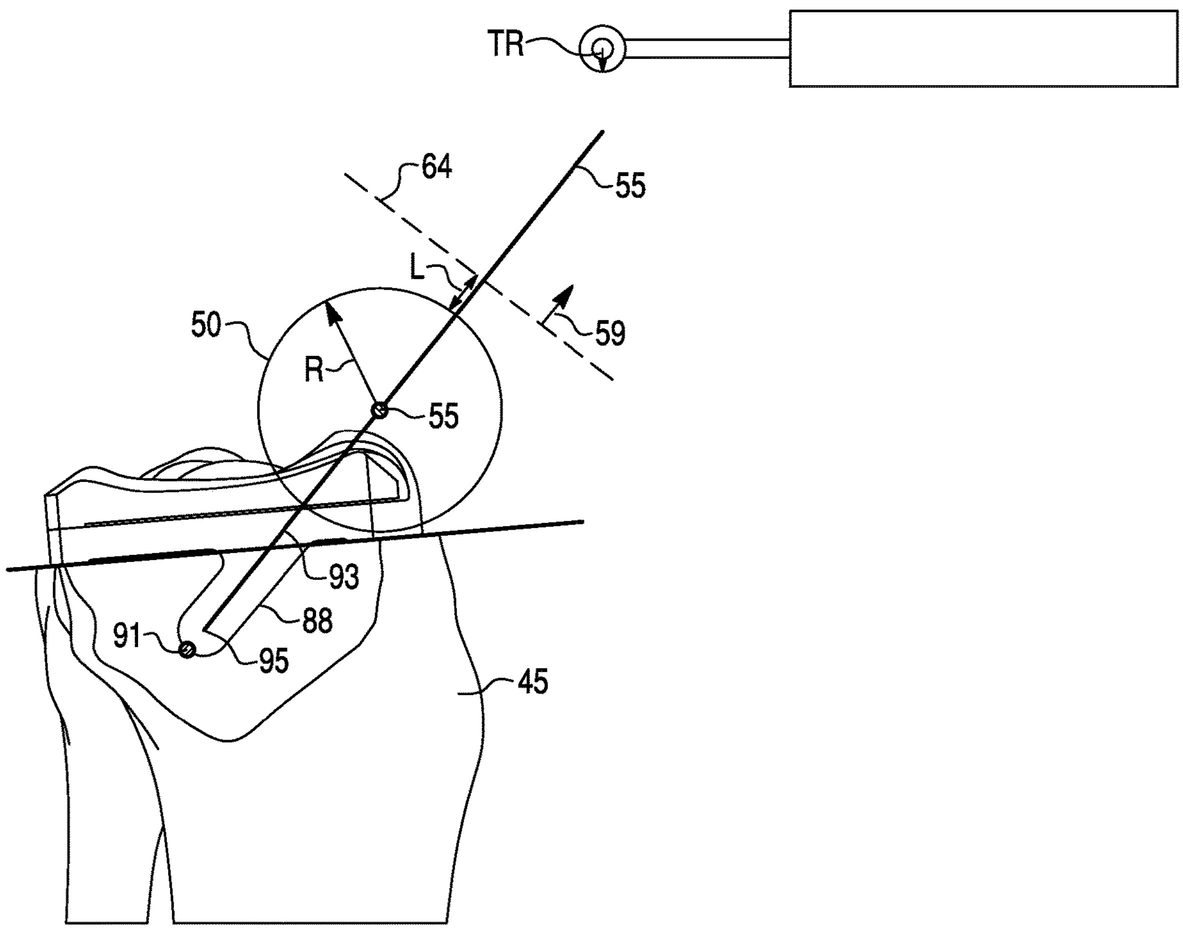


Fig. 13A

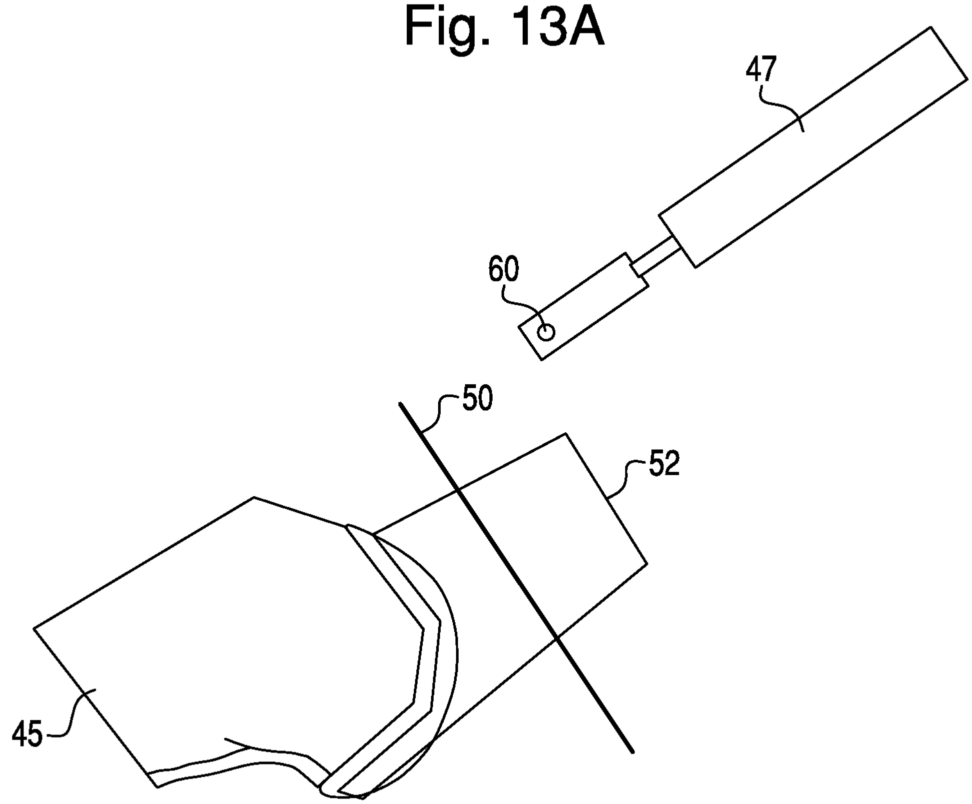


Fig. 13B

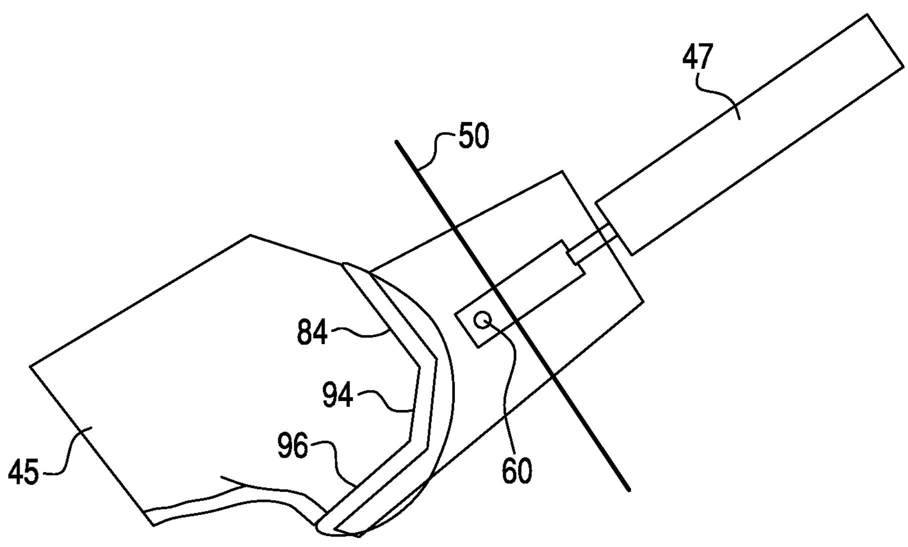


Fig. 13C

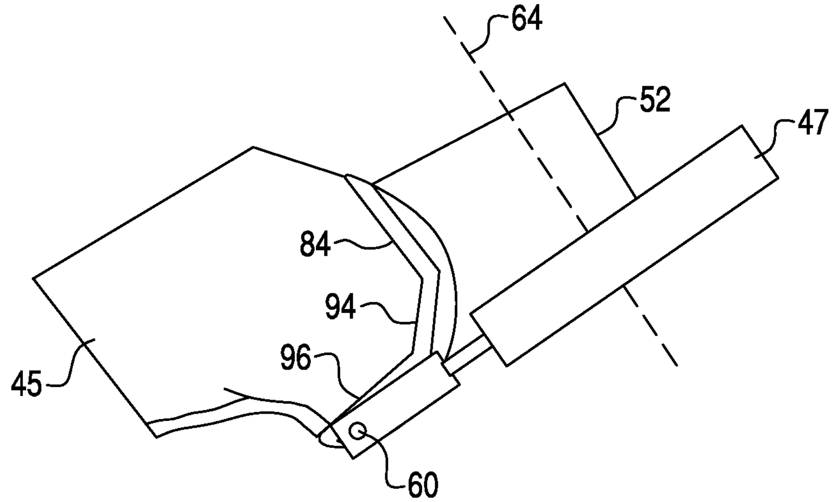


Fig. 13D

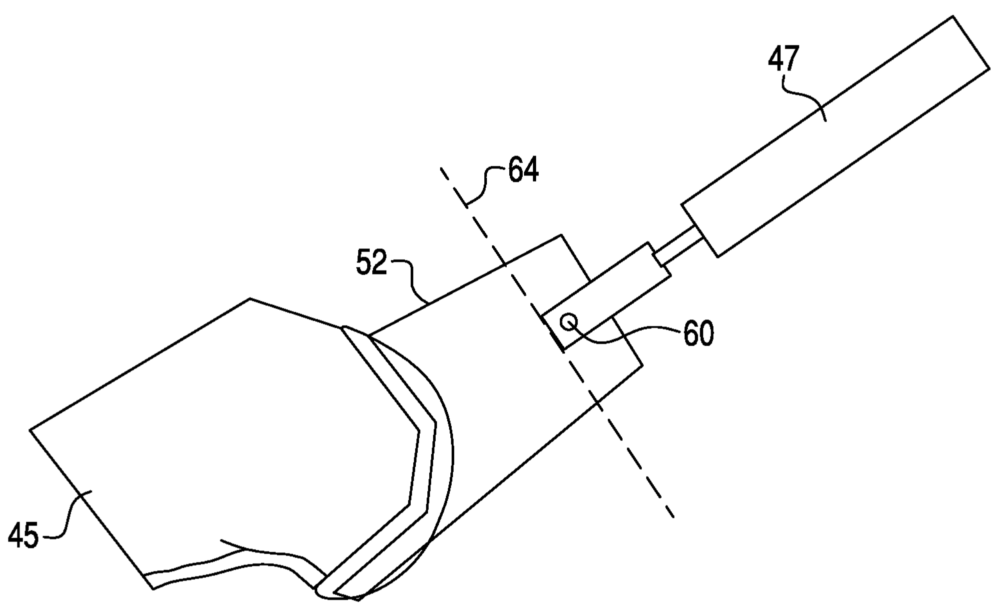


Fig. 14

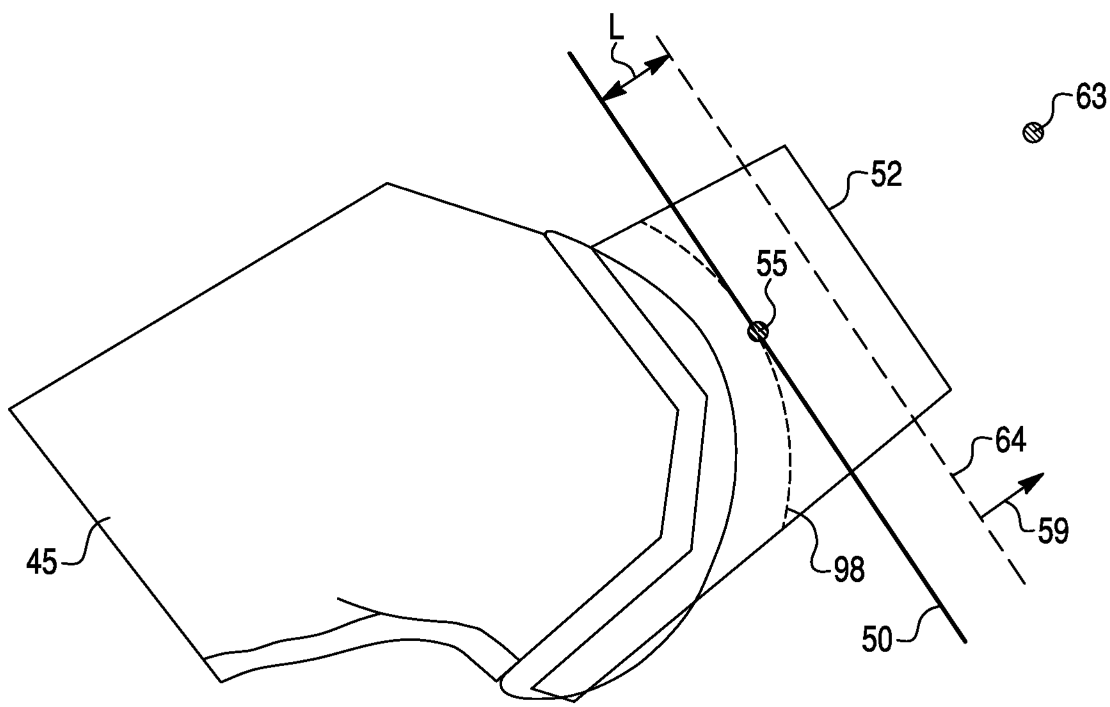


Fig. 15

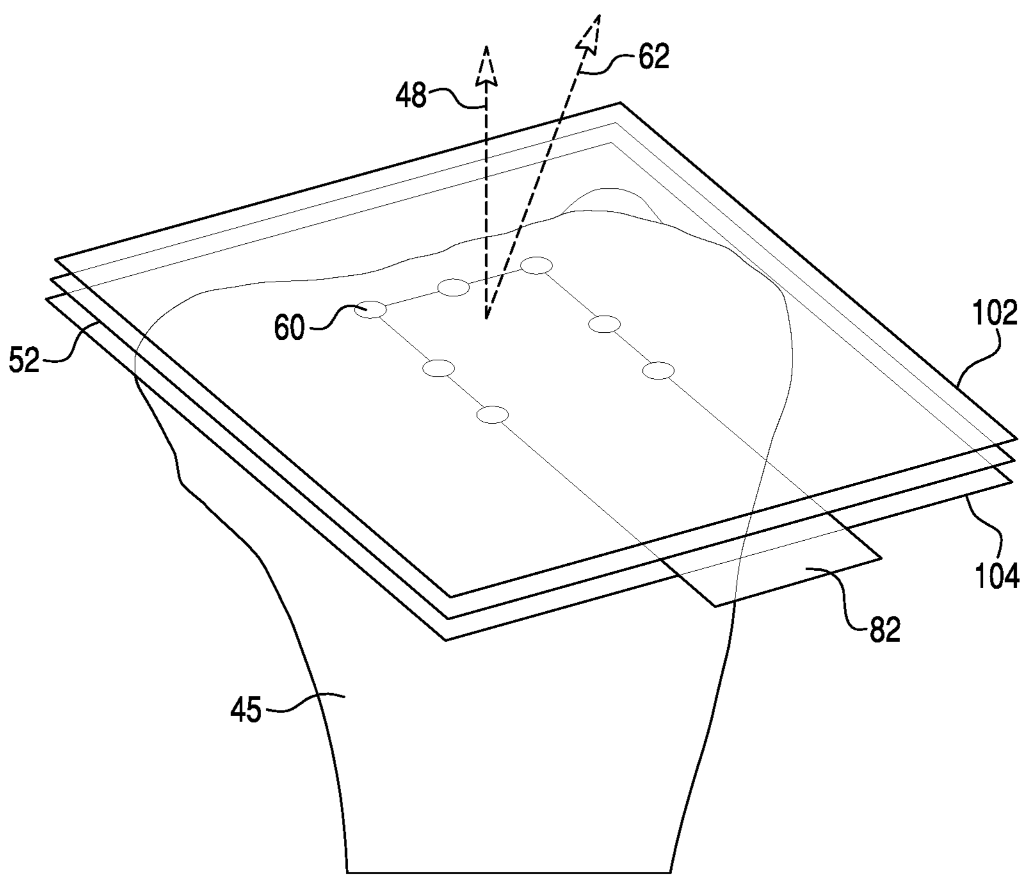
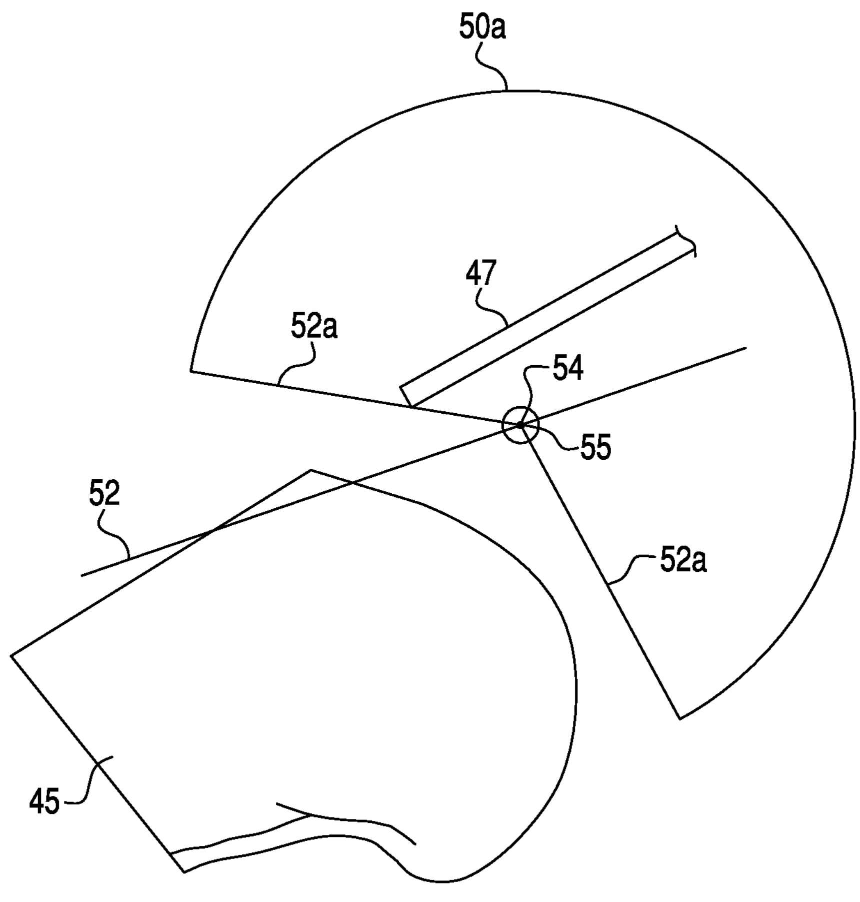


Fig. 16



SYSTEMS AND METHODS FOR HAPTIC CONTROL OF A SURGICAL TOOL

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 15/611,436, filed Jun. 1, 2017, which is a continuation of U.S. application Ser. No. 14/824,867, filed Aug. 12, 2015, which is a continuation of U.S. application Ser. No. 13/725,348, filed Dec. 21, 2012, each of which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] The present invention relates generally to the field of haptics, and more particularly to haptic control of a surgical tool.

[0003] During computer-assisted surgeries, a surgeon may utilize a haptic device. "Haptic" refers to a sense of touch, and the field of haptics relates to, among other things, human interactive devices that provide feedback to an operator. Feedback may include tactile sensations such as, for example, vibration. Feedback may also include providing force to a user, such as a positive force or a resistance to movement. A common use of haptics is to provide a user of the device with guidance or limits for manipulation of that device. For example, a haptic device may be coupled to a surgical tool, which can be manipulated by a surgeon to perform a surgical procedure. The surgeon's manipulation of the surgical tool can be guided or limited through the use of haptics to provide feedback to the surgeon during manipulation of the surgical tool.

[0004] A surgical plan is typically developed prior to performing a surgical procedure with a haptic device. The surgical plan may be patient-specific. Based on the surgical plan, the surgical system guides or limits movements of the surgical tool during portions of the surgical procedure. Control of the surgical tool serves to protect the patient and to assist the surgeon during implementation of the surgical plan.

[0005] In general, haptic devices for use during surgical procedures can have at least two modes of operation. In free mode, the surgeon can substantially freely manipulate the surgical tool coupled to the device. In haptic control mode, components of the surgical system (e.g., haptic objects) are activated to guide or limit movements of the surgical tool. Use of prior art haptic devices may be enhanced by a mechanism to improve transitions between free mode and haptic control mode during a surgical procedure.

SUMMARY

[0006] One embodiment relates to a surgical system. The surgical system includes a surgical tool and a processing circuit. The processing circuit is configured to provide a plurality of virtual haptic interaction points where each virtual haptic interaction point is associated with a portion of the surgical tool such that movement of the surgical tool corresponds to movement of the plurality of virtual haptic interaction points, establish a haptic object that defines a working boundary for the surgical tool, and constrain at least one of the portions of the surgical tool based on a relationship between at least one of the plurality of virtual haptic interaction points and the haptic object.

[0007] Another embodiment relates to a method for using a surgical system. The method includes providing a surgical tool; providing a plurality of virtual haptic interaction points associated with a plurality of portions of the surgical tool such that movement of the surgical tool corresponds to movement of the plurality of virtual haptic interaction points; establishing a haptic object that defines a working boundary for the surgical tool; and constraining at least one of the portions of the surgical tool based on a relationship between at least one of the plurality of virtual haptic interaction points and the haptic object.

[0008] A still further embodiment relates to a computer-readable storage medium having instructions thereon that, when executed by a processing circuit, aid in the planning or performance of a surgical procedure. The medium includes instructions for associating a plurality of portions of a surgical tool with a plurality of virtual haptic interaction points such that movement of the surgical tool corresponds to movement of the plurality of virtual haptic interaction points, instructions for activating a haptic object that defines a working boundary for the surgical tool, and instructions for constraining at least one of the plurality of portions of the surgical tool within the working boundary based on a relationship between at least one of the plurality of virtual haptic interaction points and the haptic object.

[0009] Alternative exemplary embodiments relate to other features and combinations of features as may be generally recited in the claims.

BRIEF DESCRIPTION OF THE FIGURES

[0010] The disclosure will become more fully understood from the following detailed description, taken in conjunction with the accompanying figures, wherein like reference numerals refer to like elements, in which:

[0011] FIG. **1** is a surgical system according to an exemplary embodiment.

[0012] FIGS. **2**A and **2**B are embodiments of a sagittal saw.

[0013] FIGS. **3**A and **3**B illustrate planned femur modifications according to an exemplary embodiment, and FIGS. **3**C and **3**D illustrate planned tibia modifications according to an exemplary embodiment.

[0014] FIG. **4** illustrates a method for using a surgical system, according to an exemplary embodiment.

[0015] FIGS. **5**A-**5**E illustrate entry and exit from haptic control when the tool normal is perpendicular to the haptic object, according to an exemplary embodiment.

[0016] FIGS. **6**A and **6**B show the haptic object of FIGS. **5**A-**5**E, according to an exemplary embodiment.

[0017] FIGS. **7**A and **7**B illustrate an offset haptic object according to an exemplary embodiment.

[0018] FIGS. **8**A-**8**E illustrate entry and exit from haptic control when the tool axis is perpendicular to the haptic object, according to an exemplary embodiment.

[0019] FIGS. **9**A and **9**B show the haptic object of FIGS. **8**A-**8**E, according to an exemplary embodiment.

[0020] FIG. **10** illustrates another embodiment of an offset haptic object, according to an exemplary embodiment.

[0021] FIGS. **11**A-**11**E illustrate entry and exit from haptic control when the haptic object is a line, according to an exemplary embodiment.

[0022] FIG. **12** illustrates various features of the surgical plan of the embodiment of FIGS. **11**A-**11**E.

[0023] FIGS. **13A-13D** illustrate entry and exit from haptic control when the haptic object is a three-dimensional volume, according to an exemplary embodiment.

[0024] FIG. **14** illustrates various features of the surgical plan of the embodiment of FIGS. **13A-13D**.

[0025] FIG. **15** illustrates a haptic restoration feature employed when haptic control is disengaged.

[0026] FIG. **16** illustrates an entry boundary, according to an exemplary embodiment.

DETAILED DESCRIPTION

[0027] Before turning to the figures, which illustrate the exemplary embodiments in detail, it should be understood that the application is not limited to the details or methodology set forth in the description or illustrated in the figures. It should also be understood that the terminology is for the purpose of description only and should not be regarded as limiting. For example, several illustrations depict methods related to haptic control entry and exit when performing specific surgical procedures on a patient's knee. However, the embodiments of haptic control described herein may be applied to haptic control of a surgical tool during any type of surgical procedure on any part of a patient, including a patient's shoulder, arm, elbow, hands, hips, legs, feet, neck, face, etc.

Exemplary Surgical System

[0028] Referring to FIG. **1**, a surgical system **100** includes a navigation system **10**, a computer **20**, and a haptic device **30**. The navigation system tracks the patient's bone, as well as surgical tools utilized during the surgery, to allow the surgeon to visualize the bone and tools on a display **24** and to enable haptic control of a surgical tool **36** coupled to the haptic device **30**.

[0029] The navigation system **10** may be any type of navigation system configured to track a patient's anatomy and surgical tools during a surgical procedure. For example, the navigation system **10** may include a non-mechanical tracking system, a mechanical tracking system, or any combination of non-mechanical and mechanical tracking systems. The navigation system **10** obtains a position and orientation (i.e. pose) of an object with respect to a coordinate frame of reference. As the object moves in the coordinate frame of reference, the navigation system tracks the pose of the object to detect movement of the object.

[0030] In one embodiment, the navigation system **10** includes a non-mechanical tracking system as shown in FIG. **1**. The non-mechanical tracking system is an optical tracking system with a detection device **12** and a trackable element (e.g. navigation marker **14**) that is disposed on a tracked object and is detectable by the detection device **12**. In one embodiment, the detection device **12** includes a visible light-based detector, such as a MicronTracker (Claron Technology Inc., Toronto, CN), that detects a pattern (e.g., a checkerboard pattern) on a trackable element. In another embodiment, the detection device **12** includes a stereo camera pair sensitive to infrared radiation and positionable in an operating room where the surgical procedure will be performed. The trackable element is affixed to the tracked object in a secure and stable manner and includes an array of markers having a known geometric relationship to the tracked object. As is known, the trackable elements may be active (e.g., light emitting diodes or LEDs) or passive (e.g., reflective spheres, a checkerboard pattern, etc.) and 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.

[0031] In operation, the detection device **12** detects positions of the trackable elements, and the surgical system **100** (e.g., the detection device **12** using embedded electronics) calculates a pose of the tracked object based on the trackable elements' positions, unique geometry, and known geometric relationship to the tracked object. The navigation system **10** includes a trackable element for each object the user desires to track, such as the navigation marker **14** located on the tibia **2**, navigation marker **16** located on the femur **4**, haptic device marker **18** (to track a global or gross position of the haptic device **30**), and an end effector marker **19** (to track a distal end of the haptic device **30**).

[0032] Referring again to FIG. **1**, the surgical system **100** further includes a processing circuit, represented in the figures as a computer **20**. The processing circuit includes a processor and memory device. The processor can be implemented as a general purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable electronic processing components. The memory device (e.g., memory, memory unit, storage device, etc.) is one or more devices (e.g., RAM, ROM, Flash memory, hard disk storage, etc.) for storing data and/or computer code for completing or facilitating the various processes and functions described in the present application. The memory device may be or include volatile memory or non-volatile memory. The memory device may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present application. According to an exemplary embodiment, the memory device is communicably connected to the processor via the processing circuit and includes computer code for executing (e.g., by the processing circuit and/or processor) one or more processes described herein.

[0033] The computer **20** is configured to communicate with the navigation system **10** and the haptic device **30**. Furthermore, the computer **20** may receive information related to surgical procedures and perform various functions related to performance of surgical procedures. For example, the computer **20** may have software as necessary to perform functions related to image analysis, surgical planning, registration, navigation, image guidance, and haptic guidance.

[0034] The haptic device **30** includes a base **32**, a robotic arm **34**, and a surgical tool **36** coupled to the robotic arm **34**. The surgical tool may be any surgical tool that can be coupled to the robotic arm **34**. For example, in the embodiment of FIG. **1**, the surgical tool **36** is a spherical burr. The surgical tool **36** may also be a sagittal saw **38**, shown in FIG. **2**A, or sagittal saw **40**, shown in FIG. **2**B. The blade **39** of sagittal saw **38** is aligned parallel to tool axis **42**, while the blade **39** of sagittal saw **40** is aligned perpendicular to tool axis **42**. The surgeon can choose between a spherical burr, sagittal saw **38**, sagittal saw **40**, or any other type of surgical tool depending on the type of bone modification (e.g. hole, planar cut, curved edge, etc.) the surgeon desires to make.

[0035] A surgeon interacts with haptic device **30** to perform surgical procedures on a patient. In general, haptic device **30** has two modes of operation. In free mode, the surgeon can substantially freely manipulate the pose of the surgical tool **36**. In haptic control mode, one or more haptic objects **52** are activated. The haptic object **52** can constrain the surgical tool **36** as described in various embodiments herein.

Development of a Surgical Plan

[0036] A surgical plan is created prior to a surgeon's performance of a surgical procedure. The surgical plan is developed utilizing a three-dimensional representation of a patient's anatomy, also referred to herein as a virtual bone model **45** (see FIGS. **3**A-**3**D). A "virtual bone model" may include virtual representations of cartilage or other tissue in addition to bone. To obtain the virtual bone model **45**, the computer **20** receives images of the patient's anatomy on which the surgical procedure is to be performed. The patient's anatomy may be scanned using any known imaging technique, such as CT, MRI, or ultrasound. The scan data is then segmented to obtain the virtual bone model **45**. For example, prior to a surgical procedure on the knee, a three-dimensional representation of the femur **4** and tibia **2** is created. Alternatively, the virtual bone model **45** may be obtained by selecting a three-dimensional model from a database or library of bone models. In one embodiment, the user may use input device **22** to select an appropriate model. In another embodiment, the computer **20** may be programmed to select an appropriate model based on images or other information provided about the patient. The selected bone model(s) from the database can then be deformed based on specific patient characteristics, creating a virtual bone model **45** for use in surgical planning and implementation as described herein.

[0037] The surgeon can create a surgical plan based on the virtual bone model **45**. The surgical plan may include the desired cuts, holes, or other modifications to a patient's bone **44** to be made by the surgeon using the surgical system **100**. The modifications may be planned based on the configuration of a component to be coupled to the bone during the surgery. For example, prior to performance of total knee arthroplasty, the surgical plan may include the planned modifications to bone illustrated in FIGS. **3**A-**3**D. FIGS. **3**A and **3**B illustrate a virtual bone model **45** of a femur **4** that includes planned modifications to the femur **4**, including anterior cut **46**, anterior chamfer cut **92**, distal cut **84**, posterior chamfer cut **94**, and posterior cut **96**. FIGS. **3**C and **3**D illustrate a virtual bone model **45** of a tibia **2** that includes planned modifications to the tibia **2**, including tibial floor cut **49**, a wall cut **51**, and a peg cut **53**. The planned modifications to the femur **4** shown in FIGS. **3**A and **3**B correspond to the virtual component **66** (FIG. **6**A), which represents a component to be coupled to the femur **4**.

[0038] The surgical plan further includes one or more haptic objects that will assist the surgeon during implementation of the surgical plan by enabling constraint of the surgical tool **36** during the surgical procedure. A haptic object **52** may be formed in one, two, or three dimensions. For example, a haptic object can be a line (FIG. **11**A), a plane (FIG. **6**B), or a three-dimensional volume (FIG. **13**A). Haptic object **52** may be curved or have curved surfaces, and can be any shape. Haptic object **52** can be created to represent a variety of desired outcomes for movement of the surgical tool **36** during the surgical procedure. For example, a haptic object **52** in the form of a line may represent a trajectory of the surgical tool **36**. A planar haptic object **52** may represent a modification, such as a cut, to be created on the surface of a bone **44**. One or more of the boundaries of a three-dimensional haptic object may represent one or more modifications, such as cuts, to be created on the surface of a bone **44**. Furthermore, portions of a three-dimensional haptic object may correspond to portions of bone to be removed during the surgical procedure.

[0039] Prior to performance of the surgical procedure, the patient's anatomy is registered to the virtual bone model **45** of the patient's anatomy by any known registration technique. One possible registration technique is point-based registration, as described in U.S. Pat. No. 8,010,180, titled "Haptic Guidance System and Method," granted Aug. 30, 2011, and hereby incorporated by reference herein in its entirety. Alternatively, registration may be accomplished by 2D/3D registration utilizing a hand-held radiographic imaging device, as described in U.S. application Ser. No. 13/562,163, titled "Radiographic Imaging Device," filed Jul. 30, 2012, and hereby incorporated by reference herein in its entirety. Registration of the patient's anatomy allows for accurate navigation and haptic control during the surgical procedure. When the patient's anatomy moves during the surgical procedure, the surgical system **100** moves the virtual bone model **45** in correspondence. The virtual bone model **45** therefore corresponds to, or is associated with, the patient's actual (i.e. physical) anatomy. Similarly, any haptic objects **52** created during surgical planning also move in correspondence with the patient's anatomy, and the haptic objects **52** correspond to locations in actual (i.e. physical) space. These locations in physical space are referred to as working boundaries. For example, a linear haptic object **52** corresponds to a linear working boundary in physical space, a planar haptic object **52** corresponds to a planar working boundary in physical space, and a three-dimensional haptic object **52** corresponds to a three-dimensional volume in physical space.

[0040] The surgical system **100** further includes a virtual tool **47** (FIG. **5**A), which is a virtual representation of the surgical tool **36**. Tracking of the surgical tool **36** by the navigation system **10** during a surgical procedure allows the virtual tool **47** to move in correspondence with the surgical tool **36**. The virtual tool **47** includes one or more haptic interaction points (HIPs), which represent and are associated with locations on the physical surgical tool **36**. As described further below, relationships between HIPs and haptic objects **52** enable the surgical system **100** to constrain the surgical tool **36**. In an embodiment in which the surgical tool **36** is a spherical burr, an HIP **60** may represent the center of the spherical burr (FIG. **11**A). If the surgical tool **36** is an irregular shape, such as sagittal saws **38** or **40** (FIGS. **2**A and **2**B), the virtual representation of the sagittal saw may include numerous HIPs. Using multiple HIPs to generate haptic forces (e.g. positive force feedback or resistance to movement) on a surgical tool is described in U.S. application Ser. No. 13/339,369, titled "System and Method for Providing Substantially Stable Haptics," filed Dec. 28, 2011, and hereby incorporated herein in its entirety. In one embodiment of the present invention, a virtual tool **47** representing a sagittal saw includes eleven HIPs. As used herein, references to an "HIP" are deemed to also include references to "one or more HIPs." For example, HIP **60** can represent one or more HIPs, and any calculations or processes based on HIP **60** include calculations or processes based on multiple HIPs.

[0041] During a surgical procedure, the surgical system **100** constrains the surgical tool **36** based on relationships between HIPs and haptic objects **52**. In general, the term "constrain," as used herein, is used to describe a tendency to restrict movement. However, the form of constraint imposed on surgical tool **36** depends on the form of the relevant haptic object **52**. A haptic object **52** may be formed in any desirable shape or configuration. As noted above, three exemplary embodiments include a line, plane, or three-dimensional volume. In one embodiment, the surgical tool **36** is constrained because HIP **60** of surgical tool **36** is restricted to movement along a linear haptic object **52**. In another embodiment, the surgical tool **36** is constrained because planar haptic object **52** substantially prevents movement of HIP **60** outside of the plane and outside of the boundaries of planar haptic object **52**. The boundaries of the planar haptic object **52** act as a "fence" enclosing HIP **60**. If the haptic object **52** is a three-dimensional volume, the surgical tool **36** may be constrained by substantially preventing movement of HIP **60** outside of the volume enclosed by the walls of the three-dimensional haptic object **52**. Because of the relationship between the virtual environment (including the virtual bone model **45** and the virtual tool **47**) and the physical environment (including the patient's anatomy and the actual surgical tool **36**), constraints imposed on HIP **60** result in corresponding constraints on surgical tool **36**.

Haptic Control During a Surgical Procedure

[0042] At the start of a surgical procedure, the haptic device **30** (coupled to a surgical tool **36**) is typically in free mode. The surgeon is therefore able to move the surgical tool **36** towards bone **44** in preparation for creation of a planned modification, such as a cut or hole. Various embodiments presented herein may facilitate the switch of haptic device **30** from free mode to haptic control mode and from haptic control mode back to free mode, which may increase the efficiency and ease of use of surgical system **100**.

[0043] One method for using a surgical system is illustrated in FIG. **4**. In step **401**, a surgical tool is provided. A virtual HIP is also provided, which is associated with the surgical tool (e.g., surgical tool **36** of FIG. **1**) such that movement of the HIP corresponds to movement of the surgical tool **36** (step **402**). The surgical method further includes providing a virtual entry boundary and a virtual exit boundary (step **403**). As described further below, entry and exit boundaries are virtual boundaries created during surgical planning, and interactions between an HIP and the entry and exit boundaries may facilitate switching haptic device **30** between free mode and haptic control mode during a surgical procedure. In other words, interactions between the HIP and entry and exit boundaries facilitate entry into and exit from haptic control. In step **404**, a haptic object is activated. The activated haptic object can constrain the surgical tool after the haptic interaction point crosses the virtual entry boundary. In step **405**, the haptic object is deactivated after the HIP crosses the virtual exit boundary. Because the haptic object may be deactivated substantially simultaneously with the HIP crossing the virtual exit boundary, the term "after" can include deactivation that occurs at substantially the same time as the HIP crosses the virtual exit boundary.

[0044] FIGS. **5**A-**5**E illustrate the virtual environment during an embodiment of entry into and exit from haptic control. In this embodiment, the virtual bone model **45** represents a femur **4**, and virtual tool **47** represents a surgical tool **36** in the form of sagittal saw **38** (e.g. as shown in FIG. **2**A). A sagittal saw **38** may be useful for creating a variety of cuts during a total knee arthroplasty, such as cuts corresponding to planned anterior cut **46**, posterior cut **96**, and tibial floor cut **49** (FIGS. **3**A-**3**D). In the embodiment illustrated in FIGS. **5**A-**5**E, the planned modification is anterior cut **46**, which corresponds to the anterior surface **68** of a virtual implant component **66** (FIG. **6**A). FIG. **3**B shows a perspective view of the planned anterior cut **46** on a virtual bone model **45**. The virtual environment depicted in FIG. **5**A includes a planar haptic object **52**. Planar haptic object **52** may also be an offset haptic object **78** (described below). Planar haptic object **52** may be any desired shape, such as the shape shown in FIG. **6**B. FIG. **6**B illustrates haptic object **52**, a blade of virtual tool **47**, and a virtual implant component **66** all superimposed on each other to aid in understanding the relationship between the various components of the surgical plan. In this embodiment, haptic object **52** represents a cut to be created on femur **4**. Haptic object **52** is therefore shown in FIGS. **6**A and **6**B aligned with anterior surface **68** of the virtual implant component **66**. The blade of virtual tool **47** is shown during haptic control mode, when haptic object **52** is activated and the blade is confined to the plane of haptic object **52**.

[0045] Referring again to FIG. **5**A, entry boundary **50** is a virtual boundary created during development of the surgical plan. Interactions between HIP **60** and the entry boundary **50** trigger the haptic device **30** to switch from free mode to "automatic alignment mode," a stage of haptic control described more fully below. The entry boundary **50** represents a working boundary in the vicinity of the patient's anatomy, and is designed and positioned such that the surgeon is able to accurately guide the surgical tool **36** to the working boundary when the haptic device **30** is in free mode. The entry boundary **50** may, but does not necessarily, enclose a portion of a haptic object **52**. For example, in FIG. **5**A, entry boundary **50** encloses a portion of haptic object **52**.

[0046] FIG. **5**A presents a cross-section of the virtual environment. In this embodiment, entry boundary **50** is pill-shaped and encloses a three-dimensional volume. The pill-shaped entry boundary **50** has a cylindrical portion with a radius R (shown in FIG. **7**A) and two hemispherical ends also having radius R (not shown). A target line **54** forms the cylinder axis (perpendicular to the page in FIG. **5**A). The target line **54** passes through a target point **55**, which is the center of entry boundary **50** in the illustrated cross section. Entry boundary **50** can also be any other shape or configuration, such as a sphere, a cube, a plane, or a curved surface.

[0047] In one embodiment, entry boundary **50** can be a "Pacman-shaped" entry boundary **50***a*, as shown in FIG. **16**. The Pacman-shaped entry boundary is formed by cutting out a segment of a pill-shaped entry boundary, as described above, to form an entry boundary **50***a* having the cross section shown in FIG. **16**. In this embodiment, the entry boundary **50***a* is therefore a three-dimensional volume shaped as a pill with a removed segment, such that a cross section of the virtual entry boundary is sector-shaped (i.e., "Pacman-shaped"). Pacman-shaped entry boundary **50***a* includes two intersecting haptic walls **52***a*. A target line **54** (perpendicular to the page in FIG. **16**) represents the intersection of haptic walls **52***a*. Target point **55** is the center of target line **54**. Haptic walls **52***a* are an embodiment of the haptic objects **52** described herein, and can therefore constrain movement of a surgical tool **36** by substantially preventing HIP **60** from crossing haptic walls **52***a*. Haptic walls **52** allow the Pacman-shaped entry boundary **50***a* to create a safe zone in front of the patient's bone. The Pacman-shaped entry boundary **50***a* can be used as the entry boundary in any of the embodiments described herein to protect the patient's bone when a surgical tool is approaching the patient. FIG. **16** illustrates virtual tool **47** (which corresponds to surgical tool **36**) as it makes contact with haptic wall **52***a*. The haptic wall **52***a* prevents the virtual tool **47** (and thus the surgical tool **36**) from crossing haptic wall **52***a* and approaching the patient's bone.

[0048] At the beginning of a surgical procedure, the surgeon guides surgical tool **36** towards the working boundary represented by entry boundary **50**. Once the surgeon causes HIP **60** of the surgical tool **36** to cross entry boundary **50**, the surgical system **100** enters automatic alignment. Prior to or during automatic alignment, the surgical system **100** performs calculations to reposition and reorient surgical tool **36**. In one embodiment, the calculations include computing distance **58** (see FIG. **5**B). If the surgical tool **36** is a spherical burr, distance **58** may represent the shortest distance line between a single HIP **60** and target line **54** (e.g. as shown in FIG. **11**B) or another reference object. When the surgical tool **36** is a sagittal saw **38** or **40**, the calculations to reposition and reorient surgical tool **36** may be based on the position of multiple HIPs relative to target line **54** or other reference object, although a distance **58** may still be calculated.

[0049] After performing the necessary calculations, the surgical system **100** is able to automatically align the surgical tool **36** from the pose of virtual tool **47** shown in FIG. **5**B to the pose of virtual tool **47** shown in FIG. **5**C. The haptic control embodiments described herein may (1) automatically modify the position of surgical tool **36** (i.e. reposition), (2) automatically modify the orientation of surgical tool **36** (i.e. reorient), or (3) both automatically reposition and reorient the surgical tool **36**. The phrase "automatic alignment" can refer to any of scenarios (1), (2), or (3), and is a general term for modifying either or both of the position and orientation of the surgical tool **36**. In the embodiment of FIGS. **5**A-**5**E, for example, automatic alignment may alter both the position and the orientation of surgical tool **36** relative to a bone **44**. Repositioning is accomplished by moving HIP **60** such that HIP **60** lies within the plane of haptic object **52**. In one embodiment, HIP **60** is repositioned to lie on target line **54**. Reorienting the surgical tool **36** may be accomplished by rotating the virtual tool **47** such that the virtual tool normal **48** is perpendicular to haptic object **52** (i.e. tool normal **48** is parallel to the haptic object normal **62**), as shown in FIG. **5**C. When the virtual tool **47** represents sagittal saw **38**, aligning the virtual tool normal **48** perpendicular to haptic object **52** causes the blade **39** of sagittal saw **38** to be accurately oriented relative to the bone **44**. However, if the cutting portion of surgical tool **36** is symmetrical, such as when surgical tool **36** is a spherical burr, it may not be necessary to reorient the surgical tool **36** during automatic alignment. Rather, surgical tool **36** might only be repositioned to bring HIP **60** within the plane of haptic object **52**. After automatic alignment is complete, surgical tool **36** is in place to perform a bone modification according to the preoperative surgical plan.

[0050] The surgical system **100** may include a safety mechanism to provide the surgeon with control during automatic alignment. The safety mechanism can be designed to require certain actions (or continuation of an action) by a user for completion of automatic alignment. In one embodiment, the surgical system **100** produces an audible noise or other alert when HIP **60** crosses entry boundary **50**. The surgical system **100** is then able to initiate automatic alignment. However, before an automatic alignment occurs, the surgeon must act by depressing a trigger or performing another action. If the trigger is released during automatic alignment, the surgical system **100** may stop any automatic movement of haptic device **30** or cause haptic device **30** to enter free mode. In another embodiment, haptic device **30** includes a sensor to sense when the surgeon's hand is present. If the surgeon removes his or her hand from the sensor during automatic alignment, the surgical system **100** may stop any automatic movement of haptic device **30** or cause haptic device **30** to enter free mode. The surgeon acts to ensure completion of automatic alignment by continuing to keep his or her hand on the sensor. These embodiments of a safety mechanism allow the surgeon to decide whether and when to enable automatic alignment, and further allows the surgeon to stop automatic alignment if another object (e.g. tissue, an instrument) is in the way of surgical tool **36** during automatic alignment.

[0051] Entry boundary **50***a* of FIG. **16** is particularly beneficial if the above-described safety mechanisms are being utilized. As one illustration, the surgeon begins the haptic control processes described herein by guiding surgical tool **36** towards the patient until the surgical tool **36** penetrates an entry boundary. The surgical system **100** then alerts the surgeon that the system is ready to begin automatic alignment. However, the surgeon may not immediately depress a trigger or perform some other action to enable the system to initiate the automatic alignment mode. During this delay, the surgical tool **36** remains in free mode, and the surgeon may continue to guide the tool towards the patient. Accordingly, entry boundary **50***a* shown in FIG. **16** includes haptic walls **52***a*. These walls **52***a* prevent the surgeon from continuing to guide the surgical tool **36** (represented by virtual tool **47**) towards the patient prior to enabling automatic alignment (e.g., via depressing a trigger or placing a hand on a sensor). The haptic walls **52***a* therefore serve as a safety mechanism to protect the patient prior to the surgical tool **36** being appropriately positioned and oriented to perform the planned bone modifications.

[0052] Referring to FIG. **5**C, automatic alignment is complete and the pose of surgical tool **36** has been correctly modified, and the haptic device **30** remains in haptic control mode. Haptic control mode, in general, can be characterized by the activation of a haptic object **52** and the imposition of a constraint on the movement of a surgical tool **36** by the haptic object **52**. Automatic alignment can therefore be a form of haptic control because haptic object **52** is activated, and surgical tool **36** is constrained to specific movements to realign surgical tool **36** based on haptic object **52**. During the stage of haptic control shown in FIG. **5**C, haptic object **52** is activated and HIP **60** is constrained within the plane defined by haptic object **52**. The surgeon can therefore move surgical tool **36** within the planar working boundary corresponding to haptic object **52**, but is constrained (e.g., prevented) from moving the surgical tool **36** outside of the planar working boundary. The surgeon performs the planned cut during haptic control mode. As the surgeon is cutting, the virtual tool **47** can move in the x-direction from the position illustrated in FIG. **5**C to the position illustrated in FIG. **5**D. The virtual tool **47** may also move back and forth in the z-direction in correspondence with movement of surgical tool **36**. However, planar haptic object **52** restricts HIP **60** (and thus surgical tool **36**) from movement in the y-direction. FIG. **6**B illustrates one embodiment of the shape of haptic object **52**, shown with virtual tool **47** of FIG. **5**C superimposed on haptic object **52**. A surgeon can reposition sagittal saw **38** within the working boundary corresponding to haptic object **52**, but the surgical system **100** prevents sagittal saw **38** from crossing the outer bounds of the working boundary. FIG. **6**A is a view of haptic object **52** aligned with anterior surface **68** of a virtual implant component **66**. As mentioned previously, the modifications to bone, and thus the haptic objects **52**, are typically planned to correspond to the configuration of a component to be coupled to the bone during the surgical procedure.

[0053] During portions of haptic control mode, an exit boundary **64** is activated (see FIGS. **5**C-**5**E). The exit boundary **64**, like the entry boundary **50**, is a virtual boundary created during development of the surgical plan. Interactions between HIP **60** and exit boundary **64** deactivate haptic object **52** and trigger the haptic device **30** to switch from haptic control mode back to free mode. The surgical system therefore remains in haptic control mode and maintains surgical tool **36** within the working boundary corresponding to haptic object **52** until HIP **60** crosses the exit boundary **64**. Once HIP **60** crosses the exit boundary **64** (e.g. by moving from the position shown in FIG. **5**D to the position shown in FIG. **5**E) the haptic object **52** deactivates and haptic device **30** switches from haptic control mode to free mode. When haptic control is released, the surgical tool **36** is no longer bound within the confines of a working boundary, but can be manipulated freely by the surgeon.

[0054] In one embodiment, the exit boundary **64** is planar, located a distance L from entry boundary **50** (see FIG. **7**A), and has an exit normal **59**. During haptic control mode, the surgical system **100** continuously calculates the distance from HIP **60** to exit boundary **64**. Because exit normal **59** points away from the patient's anatomy, the distance from HIP **60** to the exit boundary **64** will typically be negative during performance of bone modifications (e.g. cutting, drilling). However, when the value of this distance becomes positive, haptic control is released by deactivation of haptic object **52**, and the haptic device **30** enters free mode. In other embodiments, the exit boundary **64** can be curved, three-dimensional, or any configuration or shape appropriate for interacting with HIP **60** to disengage haptic control during a surgical procedure. Simultaneously or shortly after the switch to free mode, exit boundary **64** is deactivated and entry boundary **50** is reactivated. The surgeon can then reenter haptic control mode by causing surgical tool **36** to approach the patient such that HIP **60** crosses entry boundary **50**. Thus, the surgeon can move back and forth between free mode and haptic control by manipulating surgical tool **36**.

[0055] The entry boundary **50** and exit boundary **64** described in connection with the various embodiments herein provide advantages over prior art methods of haptic control. Some prior art embodiments employing haptic objects require a separate action by a user to activate and deactivate haptic objects and thus enter and exit haptic control. For example, to release an HIP from the confines of a haptic object, the user might have to press a button or perform a similar action to deactivate the haptic object. The action by the user deactivates the haptic object, which then allows the surgeon to freely manipulate the surgical tool. Use of an exit boundary as described herein eliminates the need for the surgeon to perform a separate deactivation step. Rather, the surgeon must only pull a surgical tool **36** away from the patient to automatically deactivate a haptic object **52** and exit haptic control. Embodiments of the present disclosure may therefore save time in the operating room. Furthermore, operation of a haptic device **30** may be more intuitive and user-friendly due to the surgeon being able to switch conveniently between free mode and haptic control mode.

[0056] FIGS. **7**A and **7**B illustrate haptic object **52** and offset haptic object **78**. A surgical plan may include an adjustable offset haptic object **78** to take into account characteristics of the surgical tool **36**. Use of offset haptic object **78** during haptic control mode of the haptic device **30** may provide additional accuracy during the surgical procedure by accounting for the dimensions of the surgical tool **36**. Thus, if the surgical tool **36** is a spherical burr, the offset haptic object **78** may be translated from haptic object **52** such that distance **80** (FIG. **7**B) is equivalent to the radius of the spherical burr. When offset haptic object **78** is activated, the surgical system **100** constrains HIP **60** of the spherical burr within the bounds of planar offset haptic object **78**, rather than constraining the HIP **60** of the spherical burr within the bounds of planar haptic object **52**. When constrained by the offset haptic object **78**, the edge of the spherical burr aligns with planned anterior cut **46**. Similarly, if the surgical tool **36** is a sagittal saw **38**, distance **80** may be equivalent to half the thickness t of blade **39**. FIG. **7**B illustrates virtual tool **47**. In this embodiment, virtual tool **47** is the sagittal saw **38** of FIG. **2**A and includes a virtual blade **82**. The virtual blade **82** has a thickness t equivalent to the thickness of blade **39**. When HIP **60** of virtual tool **47** is constrained to offset haptic object **78**, the bottom edge of virtual blade **82** will align with planned anterior cut **46**. The actual cut created by the sagittal saw **38** during surgery will then more closely correspond to the planned anterior cut **46** than if HIP **60** were constrained to haptic object **52** of FIG. **7**B.

[0057] In various embodiments, the surgical system **100** utilizes factors related to implementation of the surgical plan when calculating the parameters of adjustable offset haptic object **78**. One factor may be the vibrations of the surgical tool **36** during surgery, which can cause a discrepancy between the actual dimensions of a surgical tool **36** and the effective dimensions of the surgical tool **36**. For example, a spherical burr with a radius of 3 mm may remove bone as though its radius were 4 mm. The burr therefore has an effective radius of 4 mm. Similarly, due to vibrations, a blade **39** having a thickness of 2 mm may create a slot in bone having a thickness of 2.5 mm. The blade **39** therefore has an effective thickness of 2.5 mm. The offset haptic object **78** is created to take into account the effect of vibrations or other factors on surgical tool **36** to increase the accuracy of the actual bone modification created during surgery.

[0058] The offset haptic object **78** may be adjustable. Adjustability is advantageous because it allows a user to modify the offset haptic object **78** without having to redesign the original haptic object **52**. The surgical system **100** may be programmed to allow easy adjustment by the user as new information is gathered prior to or during the surgical procedure. If the surgical plan includes offset haptic object **78**, additional elements of the surgical plan may be similarly adjusted to an offset position from their originally planned positions. For example, the surgical system **100** may be programmed to translate entry boundary **50** and exit boundary **64** in the y-direction by the same distance as the offset haptic object **78** is translated from the haptic object **52**. Similarly, target line **54** and target point **55** may also be offset from their initially planned position. It is to be understood that the "haptic object **52**" referred to by many of the embodiments described herein may technically be an "offset haptic object" with respect to the original haptic object of the relevant surgical plan.

[0059] FIGS. **8**A-**8**E illustrate the virtual environment during another embodiment of entry and exit from haptic control. In this embodiment, the virtual bone model **45** represents a femur **4**. Virtual tool **47** represents a surgical tool **36** in the form of a sagittal saw **40** (e.g. as shown in FIG. **2**B). A sagittal saw **40** may be useful for performing a variety of cuts during a total knee arthroplasty, such as cuts corresponding to planned distal cut **84** and anterior chamfer cut **92**. In the embodiment of FIGS. **8**A-**8**E, the planned modification is a planned distal cut **84**, which corresponds to distal surface **72** of a virtual implant component **66** (FIG. **9**A). A perspective view of planned distal cut **84** is shown in FIG. **3**B. In this embodiment, as in the embodiment of FIGS. **5**A-**5**E, haptic object **52** represents a cut to be created on femur **4**. Haptic object **52** may be any shape developed during surgical planning, such as the shape shown in FIG. **9**B.

[0060] Referring again to FIGS. **8**A-**8**E, entry into and exit into haptic control takes place similarly as in the embodiment of FIGS. **5**A-**5**E, differing primarily in the automatic alignment and resulting orientation of surgical tool **36**. Any applicable features disclosed in connection to the embodiment of FIGS. **5**A-**5**E may also be present in the embodiment of FIG. **8**A-**8**E. In FIG. **8**A, the haptic device **30** is in free mode and entry boundary **50** is activated. As the surgeon brings the surgical tool **36** towards the patient's anatomy, the virtual tool **47** correspondingly approaches entry boundary **50**. Once HIP **60** has crossed entry boundary **50**, the surgical system **100** enters automatic alignment, during which the surgical system **100** performs the necessary calculations and then modifies the position and orientation of surgical tool **36** (e.g. from FIG. **8**B to FIG. **8**C). The position is modified to bring HIP **60** to the target line **54**, and the orientation is modified to bring tool axis **42** perpendicular to haptic object **52**. Because the blade **39** of sagittal saw **40** (FIG. **2**B) is perpendicular to the tool axis **42**, aligning the tool axis **42** perpendicular to the haptic object **52** causes the blade to lie in the x-y plane during the surgical procedure. Orientation of the tool axis **42** in this embodiment contrasts to the embodiment of FIGS. **5**A-**5**E, in which the tool axis **42** is oriented parallel to haptic object **52** during cutting (e.g., FIG. **5**C).

[0061] The surgical plan may be developed such that the surgical system **100** will orient the surgical tool **36** in any desired direction relative to haptic object **52**. The desired orientation may depend on the type of surgical tool. For example, if the surgical tool **36** is a sagittal saw, the surgical system **100** may orient the surgical tool **36** differently depending on the type of sagittal saw (e.g. sagittal saw **38** or sagittal saw **40**) or the type of cut to be created. Furthermore, in some embodiments, the tool is repositioned but not reoriented during automatic alignment. For example, if the surgical tool **36** is a spherical burr, the surgical system **100** may not need to modify the orientation of the surgical tool **36** to obtain the desired bone modification.

[0062] Once the surgical tool **36** has been automatically aligned as shown in FIG. **8**C, HIP **60** is constrained within the plane defined by haptic object **52**. Entry into this stage of haptic control can trigger activation of exit boundary **64**. The surgeon performs the cut by manipulating the surgical tool **36** within the planar working boundary corresponding to haptic object **52** in the x-direction and the z-direction. FIGS. **8**C and **8**D illustrate a change in position during cutting along the x-direction. When the surgeon moves the surgical tool **36** from the position shown in FIG. **8**D to the position shown in FIG. **8**E, HIP **60** crosses exit boundary **64**. The interaction between HIP **60** and exit boundary **64** deactivates haptic object **52**, releasing haptic control of surgical tool **36** and causing haptic device **30** to once again enter free mode. Upon crossing the exit boundary **64** or shortly thereafter, exit boundary **64** deactivates and entry boundary **50** reactivates. The surgeon can then reenter automatic alignment and haptic control during performance of bone modifications by manipulating surgical tool **36** such that HIP **60** crosses entry boundary **50**.

[0063] FIG. **10** illustrates haptic object **52** and offset haptic object **78** in relation to planned distal cut **84**. As described in connection with FIGS. **7**A and **7**B, the adjustable offset haptic object **78** may be modified depending factors such as the dimensions of surgical tool **36** or other factors related to implementation of the surgical plan. The adjustment of offset haptic object **78** can lead to adjustment of other planned features of the virtual environment, such as entry boundary **50**, target line **54**, target point **55**, and exit boundary **64**.

[0064] The surgical plans depicted in FIGS. **7**A-**7**B and **10** can be defined by various points and vectors. Normal origin point **57** lies on the original haptic object **52** and defines the origin of the haptic object normal **62** as well as the exit normal **59**. The haptic normal point **61** further defines the haptic object normal **62**, and may be located approximately 50 mm from the normal origin point **57**. The exit normal point **63** further defines the exit normal **59**, and may also be located approximately 50 mm from the normal origin point **57**. Thus, the haptic object normal **62** can be defined as the vector direction from the normal origin point **57** to the haptic normal point **61**, and the exit normal **59** can be defined as the vector direction from the normal origin point **57** to the exit normal point **63**. The target point **55** may lie on the offset haptic object **78**, and is offset from the normal origin point **57** in the direction of the haptic object normal **62** by a desired amount. As explained above, the desired amount may take into account the effective radius of a spherical burr or half of the effective thickness of a sagittal saw blade **39**. The target line **54** can be defined by target point **55** and the cross product vector of exit normal **59** and haptic object normal **62**, with endpoints on opposing edges of the offset haptic object **78**.

[0065] FIGS. **11**A-**11**E illustrate the virtual environment during another embodiment of entry and exit from haptic control. In this embodiment, the virtual bone model **45** represents a tibia **2**. Virtual tool **47** represents a surgical tool **36** in the form of a spherical burr, although the surgical tool **36** can be any tool capable of creating planned hole **88**. The planned modification is a hole **88** to receive the peg of a tibial component. The spherical burr can also be used to create holes for receiving pegs of femoral, patellofemoral, or any other type of implant component. In FIGS. **11A-11E**, a virtual tibial component **90** is superimposed on the bone model **45** to more clearly illustrate the planned bone modifications. In this embodiment, haptic object **52** is a line. The placement of linear haptic object **52** may be planned based on the dimensions or effective dimensions of surgical tool **36**, such as the radius TR of a spherical burr (FIG. **12**). For example, a space equivalent to radius TR may be left between the end **95** of haptic object **52** and the bottom of peg tip point **91**, as illustrated in FIG. **12**.

[0066] FIG. **11A** illustrates the virtual environment when haptic device **30** is in free mode. At the start of a surgical procedure, the surgeon moves surgical device **36** (FIG. **1**) towards the patient until HIP **60** crosses entry boundary **50** (FIG. **11B**). In this embodiment, entry boundary **50** is a sphere having a radius R (FIG. **12**) and having a target point **55** at its center. Once HIP **60** crosses entry boundary **50**, the surgical system automatically aligns surgical tool **36**. In one embodiment, the surgical system **100** calculates the shortest distance from HIP **60** to target point **55** and then repositions HIP **60** onto target point **55**. The surgical system **100** may also reorient surgical tool **36** such that tool axis **42** is parallel to haptic object **52** (FIG. **11C**). HIP **60** is then constrained to movement along linear haptic object **52**, and the surgeon can move surgical tool **36** along a linear working boundary corresponding to haptic device **52** to create hole **88** (FIG. **11D**).

[0067] As in previous embodiments, the exit boundary **64** is activated during portions of haptic control. When the surgeon desires to release haptic control, the surgical tool **36** can be moved until HIP **60** crosses exit boundary **64** (FIG. **11E**). Haptic object **52** is then deactivated, releasing haptic control and causing the haptic device **30** to reenter free mode. As discussed in relation to other embodiments, the surgical system **100** may continuously calculate the distance between HIP **60** and exit boundary **64**, releasing haptic control when this distance becomes positive. Also as described in connection with previous embodiments, entry boundary **50** can be reactivated after release of haptic control. The surgeon can then reenter haptic control by manipulating surgical tool **36** such that HIP **60** crosses entry boundary **50**.

[0068] FIG. **12** illustrates additional features of a surgical plan having a linear haptic object **52**, such as the surgical plan of FIGS. **11A-11E**. The peg axis is a line from peg tip point **91**, located on the tip of planned hole **88**, to target point **55**. Linear haptic object **52** may be a line on the peg axis having a first endpoint at end **95** and a second endpoint located past the target point **55** along the exit normal **59**. For example, the second endpoint of haptic object **52** may located 50 mm past the target point **55** in the direction of exit normal **59**. The exit boundary **64** may be planar, located a distance L from the entry boundary **50**, and have an exit normal **59** defined as the vector direction from the peg tip point **91** to the target point **55**.

[0069] FIGS. **13A-13D** illustrate another embodiment of entry into and exit from haptic control. In this embodiment, haptic object **52** is a three-dimensional volume. Virtual bone model **45** can represent any bone **44**, such as a femur **4**, and virtual tool **47** can represent any type of surgical tool **36** for performing any type of bone modifications. In the virtual environment of FIG. **13A**, haptic device **30** is in free mode. To enter haptic control, the user manipulates surgical tool **36** towards the patient's anatomy. Virtual tool **47**, including HIP **60**, move in correspondence towards entry boundary **50**. In this embodiment, entry boundary **50** is a plane that includes target point **55** (not shown). If HIP **60** is within haptic object **52** and HIP **60** crosses entry boundary **50**, as shown in FIG. **13B**, haptic control is engaged. In haptic control mode, HIP **60** is prevented from exiting the confines of the three-dimensional volume defined by haptic object **52**. Further, engagement of haptic control triggers deactivation of entry boundary **50** and activation of exit boundary **64** (FIG. **13C**).

[0070] The embodiment of FIGS. **13A-13D** does not include automatic alignment. In other words, neither the position nor the orientation of surgical tool **36** is modified during haptic control. Consequently, HIP **60** can be freely moved to any position within haptic object **52**, and the orientation of surgical tool **36** is not constrained by a haptic object. During haptic control, the surgeon can freely move surgical tool **36** within the working volume corresponding to haptic object **52** to perform the necessary bone modifications, such as cuts corresponding to planned distal cut **84**, planned posterior chamfer cut **92**, and planned posterior cut **96**. FIG. **13C** illustrates virtual tool **47** as the surgeon is creating a cut corresponding to planned posterior cut **96**. During haptic control in the embodiment of FIGS. **13A-13D**, as in previous embodiments, when HIP **60** crosses exit boundary **64** (FIG. **13D**), haptic control is released and the haptic device **30** enters free mode. In alternative embodiments, the virtual environment depicted in FIGS. **13A-13D** includes additional mechanisms to control the position of HIP **60**. For example, planar haptic objects along planned cuts **84**, **94**, and **96** could constrain HIP **60** to movement along these planar haptic objects. The virtual environment might also include mechanisms to control the orientation of virtual tool **47** (and therefore, of surgical tool **36**), such as additional planar or linear haptic objects on which HIP **60** can be constrained.

[0071] FIG. **14** illustrates the surgical plan of FIGS. **13A-13D**. Exit boundary **64** is parallel to entry boundary **50** and is located a distance L from entry boundary **50** in the direction of exit normal **59**. Exit normal **59** is the vector direction from target point **55** to exit normal point **63**. FIG. **14** further includes a prior art haptic object **98**. In a prior art method of haptic control, a user could not cause an HIP to exit haptic object **98** without performing a separate action to disengage haptic control, such as a pressing a button on input device **22** (FIG. **1**). In contrast to prior art haptic object **98**, the volumetric haptic object **52** extends farther from the planned cutting surface. Further, the surgical plan associated with haptic object **52** includes an entry boundary **50** and an exit boundary **64**. In the presently disclosed embodiments, when the surgeon pulls surgical tool **36** away from the patient and causes HIP **60** to cross exit boundary **64**, the surgical system **100** automatically deactivates haptic object **52** to release haptic control. The provision of an exit boundary **64** therefore allows the surgeon greater freedom to release haptic control during surgery. In addition, the interaction between activation and deactivation of the entry boundary **50** and exit boundary **64** described herein allows the surgeon to seamlessly and intuitively enter and exit haptic control by manipulating surgical tool **36**, without having to perform separate actions to trigger entry into and exit from haptic control.

[0072] FIG. **15** illustrates a haptic restoration feature that may be employed in any of the haptic control embodiments described herein. The haptic restoration feature is applicable when haptic control is disengaged for a reason other than because HIP **60** has crossed the exit boundary. Disengagement of haptic control might occur for various reasons, one of which relates to a temporary inability of the navigation system **10** to detect the pose of one or more tracked objects. For example, some navigation systems require a clear path between a detection device **12** and the trackable elements, such as navigation markers **14** and **16**, haptic device marker **18**, and end effector marker **19** (FIG. **1**). If one of the trackable elements is temporarily blocked (i.e. occluded), the navigation system **10** may not be able to effectively determine the pose of one or more tracked objects. As a safety precaution, when a trackable element becomes occluded during a surgical procedure, the surgical system **100** may disengage haptic control of the surgical tool **36**. Haptic control may also be disengaged due to sudden movement of a tracked object. For example, the patient's leg or the robotic arm **34** may be bumped, and the navigation system **10** is unable to accurately track the suddenly-moved object. The surgical system will therefore disengage haptic control of the surgical tool **36**. Disengagement of haptic control causes the haptic device **30** to enter free mode. The haptic restoration feature can then be utilized to either reengage haptic control by reactivating haptic object **52** or to retain the haptic device **30** in free mode and require the surgeon to reenter entry boundary **50**.

[0073] To determine whether to reengage haptic control or whether to retain the haptic device **30** in free mode, the surgical system **100** is programmed to evaluate whether various conditions are met after the occlusion, sudden movement, or other factor has caused disengagement of haptic control. In general, the conditions may relate to the position or orientation of a surgical tool **36** relative to the desired, constrained position or orientation of surgical tool **36**, and the conditions may depend on the type of surgical tool **36** and the configuration of haptic object **52**. Three possible conditions to evaluate may be the tool's orientation, vertical penetration in a haptic plane, and whether all HIPs are within the haptic boundaries. For example, the embodiment of FIG. **15** includes a virtual blade **82**, which represents a sagittal saw and includes multiple HIPs (as indicated above, although only one HIP **60** is labeled, references to HIP **60** include references to multiple HIPs). FIG. **15** also includes a planar haptic object **52**. In this embodiment, the haptic restoration feature may include determining the orientation of virtual blade **82** relative to haptic object **52** by calculating the angle between tool normal **48** and haptic object normal **62**. Tool normal **48** and haptic object normal **62** are ideally parallel if the surgical tool **36** is being constrained during cutting to lie within the working boundary corresponding to planar haptic object **52**. One condition may be, for example, whether tool normal **48** and haptic object normal **62** are within two degrees of each other. The surgical system **100** can be programmed to conclude that if this condition is met, the orientation of surgical tool **36** remains substantially accurate even after the temporary occlusion of a trackable element or sudden movement of the patient or robotic arm. The surgical system **100** may also evaluate the position of HIP **60** relative to planar haptic object **52** (e.g., vertical penetration). FIG. **15** illustrates virtual boundaries **102**, **104** above and below haptic object **52**. Virtual boundaries **102**, **104**, can be planned to lie, for example, approximately **0**.5mm away from haptic object **52**. A second condition may be whether HIP **60** lies between these virtual boundaries **102**, **104**. As another example, a third condition may be whether each of the HIPs **60** of virtual blade **82** lie within the outer bounds of haptic object **52**.

[0074] If each of the relevant conditions are met, the haptic restoration feature reactivates haptic object **52**, which reengages haptic control and allows the surgeon to continue cutting. However, if any of the conditions are not met, the haptic device **30** remains in free mode. The surgeon must then cause HIP **60** to cross back into an entry boundary **50** (not shown in FIG. **15**), as described in the various embodiments herein. Once HIP **60** crosses entry boundary **50**, haptic control can be reengaged. In the embodiment illustrated in FIG. **15**, haptic control after HIP **60** has crossed entry boundary **50** may include automatic alignment and subsequent constraint of HIP **60** on planar haptic object **52**. In other embodiments, such as the embodiment of FIGS. **13**A-**13**D, haptic control after HIP **60** crosses entry boundary **50** may not include automatic alignment.

[0075] The construction and arrangement of the systems and methods as shown in the various exemplary embodiments are illustrative only. Although only a few embodiments have been described in detail in this disclosure, many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, use of materials, colors, orientations, etc.). For example, the position of elements may be reversed or otherwise varied and the nature or number of discrete elements or positions may be altered or varied. Accordingly, all such modifications are intended to be included within the scope of the present disclosure. The order or sequence of any process or method steps may be varied or re-sequenced according to alternative embodiments. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions and arrangement of the exemplary embodiments without departing from the scope of the present disclosure.

[0076] The present disclosure contemplates methods, systems and program products on any machine-readable media for accomplishing various operations. The embodiments of the present disclosure may be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage, other magnetic storage devices, solid state storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a machine, the machine properly views the connection as a machine-readable medium. Thus, any such connection is properly termed a machine-readable medium. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0077] Although a specific order of method steps may be described, the order of the steps may differ from what is described. Also, two or more steps may be performed concurrently or with partial concurrence (e.g. deactivation of entry boundary **50** and activation of exit boundary **64**). Such variation will depend on the software and hardware systems chosen and on designer choice. All such variations are within the scope of the disclosure. Likewise, software implementations could be accomplished with standard programming techniques with rule based logic and other logic to accomplish any connection steps, processing steps, comparison steps, and decision steps.

What is claimed is:

1. A surgical system, comprising:
- a robotic device configured to hold a surgical end effector, wherein the robotic device is configured to:
  - automatically reposition the surgical end effector to a first predefined plane in a first mode;
  - confine manual repositioning of the surgical end effector to the predefined plane in a second mode; and
- a controller configured to:
  - initiate the first mode in response to a signal indicative of a user action; and
  - initiate the second mode in response to arrival of the surgical end effector at the predefined plane via automatic repositioning in the first mode.

2. The surgical system of claim **1**, further comprising an input device configured to provide the signal indicative of the user action when the input device is engaged by a user.

3. The surgical system of claim **1**, wherein the controller is configured to control the robotic device to stop movement of the robotic device in response to removal of the signal indicative of the user action in the first mode.

4. The surgical system of claim **1**, wherein the predefined plane is positioned relative to a tracked anatomical feature.

5. The surgical system of claim **1**, wherein the controller is further configured to:
- control the robotic device in a third mode to move the surgical end effector to a second predefined plane different from the first predefined plane; and
- control the robotic device in a fourth mode to confine the manual repositioning of the surgical end effector to the second predefined plane.

6. The surgical system of claim **5**, wherein the first predefined plane aligns with a first tracked bone and the second predefined plane aligns with a second tracked bone.

7. The surgical system of claim **1**, wherein robotic device is further configured to be controlled in accordance with a third mode, the third mode distinct from the first mode and the second mode.

8. The surgical system of claim **1**, wherein the surgical end effector is configured to directly modify an anatomy of a patient.

9. The surgical system of claim **1**, wherein the controller is configured to exit the second mode in response to a removal of the signal indicative of the user action.

10. The surgical system of claim **9**, further comprising a tracking system configured to provide data indicative of a position of a joint of the patient.

11. The surgical system of claim **1**, wherein the first mode comprises automatically repositioning the surgical end effector to a point on the plane having a predefined relationship with a target.

12. The surgical system of claim **1**, wherein the first mode comprises automatically repositioning the surgical end effector into alignment with a virtual haptic object.

13. The surgical system of claim **1**, wherein the first mode comprises automatically repositioning the surgical end effector by rotating the surgical end effector.

14. The surgical system of claim **1**, wherein the robotic device comprises a base and a robotic arm extending from the base to the end effector.

15. A non-transitory computer-readable memory device storing instructions that, when executed by a processor, cause the processor to perform operations comprising:
- controlling a robotic device in a first mode in response to a signal indicative of a user action, the first mode comprising automatically moving a surgical end effector coupled to the robotic device into alignment with a predefined plane; and
- controlling the robotic device in a second mode in response to arrival of the surgical end effector at the predefined plane via automatic repositioning in the first mode, the second mode comprising confining manual repositioning of the surgical end effector to the predefined plane.

16. The non-transitory computer-readable memory device of claim **15**, wherein the operations further comprise controlling the robotic device to stop movement of the end effector in response to removal of the signal indicative of the user action in the first mode.

17. The non-transitory computer-readable memory device of claim **15**, wherein the predefined plane is positioned relative to a tracked anatomical feature.

18. The non-transitory computer-readable memory device of claim **15**, wherein the first mode comprises automatically repositioning the surgical end effector to a point having a predefined relationship with a target and positioned on the predefined plane.

19. A method of performing a bone resection, comprising:
- controlling a robotic device in a first mode in response to a signal indicative of a user action, the first mode comprising automatically repositioning a surgical end effector coupled to the robotic device to a first predefined plane; and
- controlling the robotic device in a second mode in response to arrival of the surgical end effector at the first predefined plane via automatic repositioning in the first mode, the second mode comprising confining manual repositioning of the surgical end effector to the first predefined plane.

20. The method of claim **19**, further comprising controlling the robotic device to stop movement of the robotic device in response to removal of the signal indicative of the user action in the first mode.

21. The method of claim **19**, further comprising:

executing a first cut associated with the first predefined plane;

following execution of the first cut, controlling the robotic device to automatically align with a second predefined plane; and

in response to automatic alignment with the second predefined plane, controlling the robotic device to confine manual movement to the second predefined plane.

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