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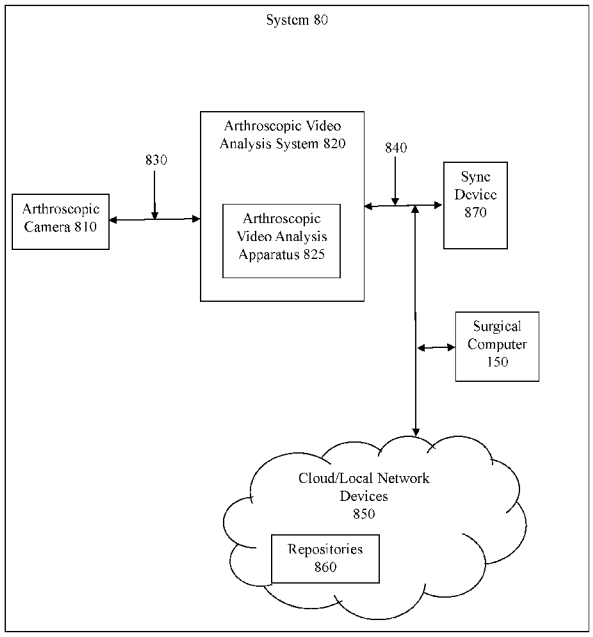


FIG. 8

(57) Abstract: Methods, non-transitory computer readable media, and arthroscopic video analysis apparatuses and systems that facilitate improved analysis of videos of arthroscopic procedures are disclosed. With this technology, analytical data related to the video feed of an arthroscopic surgery can be obtained using machine learning models and associated with the video feed. The generated videos can be output in real-time to provide contextual information related to the surgical procedure, or can be saved for playback for training or informational purposes.

[Continued on next page]

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METHODS FOR ARTHROSCOPIC VIDEO ANALYSIS AND DEVICES THEREFOR

RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Provisional Patent Application No. 62/978,939, entitled "METHODS FOR ARTHROSCOPIC VIDEO ANALYSIS AND DEVICES THEREFOR," filed February 20, 2020 and to U.S. Provisional Patent Application No. 63/111,853 entitled "METHODS FOR ARTHROSCOPIC VIDEO ANALYSIS AND DEVICES THEREFOR," filed November 10, 2020, both of which are hereby incorporated by reference herein in their entirety.

TECHNICAL FIELD

[0002] The present disclosure relates generally to methods, systems, and apparatuses related to arthroscopic video analysis and, more particularly, to methods and devices for improved processing of arthroscopic video data to identify anatomical structures, identify pathology, and to measure geometry of the anatomical structures.

BACKGROUND

[0003] Arthroscopic surgery is useful in the treatment of a number of joint-related pathologies. The core of arthroscopy is the visualization platform as it provides a window into the joint. For a skilled surgeon, a wealth of information can be extracted from the image alone. When combined into a video sequence, even more information may be extracted. Example features a skilled surgeon can determine from the video sequence of the arthroscopic surgery include identification of the anatomy while viewing only a portion of the macro structure, pathology related to a particular anatomical structure, and approximation of measurements associated with the visual field.

[0004] However, a contextual understanding of the arthroscopic field of view is constrained to a highly skilled surgeon. The problem is only exacerbated when trying to obtain a contextual understanding of the obtained images or video of the arthroscopic field of view in real-time (*i.e.*, at the refresh rate of the monitor displaying the arthroscopic field of view). While machine learning and artificial intelligence have been applied to the analysis of images obtained from fixed-orientation inputs, such as x-ray, MRI, or CT-scan images, such analytics have not been

applied to arthroscopic video given the complexity required for processing the video data in real-time. As a result, most surgeons do not record a live feed of the arthroscopic surgery, and instead primarily take short video clips or image snapshots at specific points in the surgery. These items merely memorialize which anatomical structures were implicated or which products were implanted, but they do not provide any useful data intraoperatively.

[0005] What are needed are methods and systems for providing arthroscopic video analysis that allows for the presentation of real-time analytics during an arthroscopic surgery. The analytics may be useful in labelling anatomical structures, identifying pathologies, and measuring the geometry of items in the arthroscopic field of view. Such analytics additionally may be employed when using computer-assisted surgical systems.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The accompanying drawings, which are incorporated in and form a part of the specification, illustrate the embodiments of the invention and together with the written description serve to explain the principles, characteristics, and features of the invention. In the drawings:

[0007] FIG. 1 depicts an operating theatre including an illustrative computer-assisted surgical system (CASS) in accordance with an embodiment.

[0008] FIG. 2 depicts an example of an electromagnetic sensor device according to some embodiments.

[0009] FIG. 3A depicts an alternative example of an electromagnetic sensor device, with three perpendicular coils, according to some embodiments.

[0010] FIG. 3B depicts an alternative example of an electromagnetic sensor device, with two nonparallel, affixed coils, according to some embodiments.

[0011] FIG. 3C depicts an alternative example of an electromagnetic sensor device, with two nonparallel, separate coils, according to some embodiments.

[0012] FIG. 4 depicts an example of electromagnetic sensor devices and a patient bone according to some embodiments.

[0013] FIG. 5A depicts illustrative control instructions that a surgical computer provides to other components of a CASS in accordance with an embodiment.

[0014] FIG. 5B depicts illustrative control instructions that components of a CASS provide to a surgical computer in accordance with an embodiment.

[0015] FIG. 5C depicts an illustrative implementation in which a surgical computer is connected to a surgical data server via a network in accordance with an embodiment.

[0016] FIG. 6 depicts an operative patient care system and illustrative data sources in accordance with an embodiment.

[0017] FIG. 7A depicts an illustrative flow diagram for determining a pre-operative surgical plan in accordance with an embodiment.

[0018] FIG. 7B depicts an illustrative flow diagram for determining an episode of care including pre-operative, intraoperative, and post-operative actions in accordance with an embodiment.

[0019] FIG. 7C depicts illustrative graphical user interfaces including images depicting an implant placement in accordance with an embodiment.

[0020] FIG. 8 depicts a system for arthroscopic video analysis including an arthroscopic video analysis system in accordance with an embodiment.

[0021] FIG. 9 depicts more detailed view of the arthroscopic video analysis system shown in FIG. 8 in accordance with an embodiment.

[0022] FIG. 10 depicts an exemplary arthroscopic video analysis apparatus in accordance with an embodiment.

[0023] FIG. 11 depicts a flowchart of an exemplary method for improved arthroscopic video analysis using machine learning models in accordance with an embodiment.

[0024] FIG. 12 depicts a flowchart of an exemplary workflow for the method of FIG. 11 for improved arthroscopic video analysis using post-operative video processing in accordance with an embodiment.

[0025] FIG. 13 depicts a flowchart of an exemplary workflow for the method of FIG. 11 for improved arthroscopic video analysis using intraoperative, real-time video analysis in accordance with an embodiment.

DETAILED DESCRIPTION

[0026] The present disclosure describes methods of improved arthroscopic video data analysis that associates analytical information with a video feed output. In the following description, for purposes of explanation, numerous specific details are set forth in order to

provide a thorough understanding of example embodiments. It will be evident to one skilled in the art, however, that embodiments can be practiced without any number of these specific details.

[0027] This disclosure is not limited to the particular systems, devices and methods described, as these may vary. The terminology used in the description is for the purpose of describing the particular versions or embodiments only, and is not intended to limit the scope.

[0028] As used in this document, the singular forms "a," "an," and "the" include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art. Nothing in this disclosure is to be construed as an admission that the embodiments described in this disclosure are not entitled to antedate such disclosure by virtue of prior invention. As used in this document, the term "comprising" means "including, but not limited to."

[0029] Definitions

[0030] For the purposes of this disclosure, the term "implant" is used to refer to a prosthetic device or structure manufactured to replace or enhance a biological structure. For example, in a total hip replacement procedure a prosthetic acetabular cup (implant) is used to replace or enhance a patients worn or damaged acetabulum. While the term "implant" is generally considered to denote a man-made structure (as contrasted with a transplant), for the purposes of this specification an implant can include a biological tissue or material transplanted to replace or enhance a biological structure.

[0031] For the purposes of this disclosure, the term "real-time" is used to refer to calculations or operations performed on-the-fly as events occur or input is received by the operable system. However, the use of the term "real-time" is not intended to preclude operations that cause some latency between input and response, so long as the latency is an unintended consequence induced by the performance characteristics of the machine.

[0032] Although much of this disclosure refers to surgeons or other medical professionals by specific job title or role, nothing in this disclosure is intended to be limited to a specific job title or function. Surgeons or medical professionals can include any doctor, nurse, medical professional, or technician. Any of these terms or job titles can be used interchangeably with the

user of the systems disclosed herein unless otherwise explicitly demarcated. For example, a reference to a surgeon could also apply, in some embodiments to a technician or nurse.

[0033] The systems, methods, and devices disclosed herein are particularly well adapted for surgical procedures that utilize surgical navigation systems, such as the NAVIO® surgical navigation system. NAVIO is a registered trademark of BLUE BELT TECHNOLOGIES, INC. of Pittsburgh, PA, which is a subsidiary of SMITH & NEPHEW, INC. of Memphis, TN.

[0034] CASS Ecosystem Overview

[0035] FIG. 1 provides an illustration of an example computer-assisted surgical system (CASS) 100, according to some embodiments. As described in further detail in the sections that follow, the CASS uses computers, robotics, and imaging technology to aid surgeons in performing orthopedic surgery procedures such as total knee arthroplasty (TKA) or total hip arthroplasty (THA). For example, surgical navigation systems can aid surgeons in locating patient anatomical structures, guiding surgical instruments, and implanting medical devices with a high degree of accuracy. Surgical navigation systems such as the CASS 100 often employ various forms of computing technology to perform a wide variety of standard and minimally invasive surgical procedures and techniques. Moreover, these systems allow surgeons to more accurately plan, track and navigate the placement of instruments and implants relative to the body of a patient, as well as conduct pre-operative and intraoperative body imaging.

[0036] An Effector Platform 105 positions surgical tools relative to a patient during surgery. The exact components of the Effector Platform 105 will vary, depending on the embodiment employed. For example, for a knee surgery, the Effector Platform 105 may include an End Effector 105B that holds surgical tools or instruments during their use. The End Effector 105B may be a handheld device or instrument used by the surgeon (e.g., a NAVIO® hand piece or a cutting guide or jig) or, alternatively, the End Effector 105B can include a device or instrument held or positioned by a Robotic Arm 105A. While one Robotic Arm 105A is illustrated in FIG. 1, in some embodiments there may be multiple devices. As examples, there may be one Robotic Arm 105A on each side of an operating table T or two devices on one side of the table T. The Robotic Arm 105A may be mounted directly to the table T, be located next to the table T on a floor platform (not shown), mounted on a floor-to-ceiling pole, or mounted on a wall or ceiling of an operating room. The floor platform may be fixed or moveable. In one particular

embodiment, the robotic arm 105A is mounted on a floor-to-ceiling pole located between the patient's legs or feet. In some embodiments, the End Effector 105B may include a suture holder or a stapler to assist in closing wounds. Further, in the case of two robotic arms 105A, the surgical computer 150 can drive the robotic arms 105A to work together to suture the wound at closure. Alternatively, the surgical computer 150 can drive one or more robotic arms 105A to staple the wound at closure.

[0037] The Effector Platform 105 can include a Limb Positioner 105C for positioning the patient's limbs during surgery. One example of a Limb Positioner 105C is the SMITH AND NEPHEW SPIDER2 system. The Limb Positioner 105C may be operated manually by the surgeon or alternatively change limb positions based on instructions received from the Surgical Computer 150 (described below). While one Limb Positioner 105C is illustrated in FIG. 1, in some embodiments there may be multiple devices. As examples, there may be one Limb Positioner 105C on each side of the operating table T or two devices on one side of the table T. The Limb Positioner 105C may be mounted directly to the table T, be located next to the table T on a floor platform (not shown), mounted on a pole, or mounted on a wall or ceiling of an operating room. In some embodiments, the Limb Positioner 105C can be used in non-conventional ways, such as a retractor or specific bone holder. The Limb Positioner 105C may include, as examples, an ankle boot, a soft tissue clamp, a bone clamp, or a soft-tissue retractor spoon, such as a hooked, curved, or angled blade. In some embodiments, the Limb Positioner 105C may include a suture holder to assist in closing wounds.

[0038] The Effector Platform 105 may include tools, such as a screwdriver, light or laser, to indicate an axis or plane, bubble level, pin driver, pin puller, plane checker, pointer, finger, or some combination thereof.

[0039] Resection Equipment 110 (not shown in FIG. 1) performs bone or tissue resection using, for example, mechanical, ultrasonic, or laser techniques. Examples of Resection Equipment 110 include drilling devices, burring devices, oscillatory sawing devices, vibratory impaction devices, reamers, ultrasonic bone cutting devices, radio frequency ablation devices, reciprocating devices (such as a rasp or broach), and laser ablation systems. In some embodiments, the Resection Equipment 110 is held and operated by the surgeon during surgery. In other embodiments, the Effector Platform 105 may be used to hold the Resection Equipment 110 during use.

[0040] The Effector Platform 105 can also include a cutting guide or jig 105D that is used to guide saws or drills used to resect tissue during surgery. Such cutting guides 105D can be formed integrally as part of the Effector Platform 105 or Robotic Arm 105A, or cutting guides can be separate structures that can be matingly and/or removably attached to the Effector Platform 105 or Robotic Arm 105A. The Effector Platform 105 or Robotic Arm 105A can be controlled by the CASS 100 to position a cutting guide or jig 105D adjacent to the patient's anatomy in accordance with a pre-operatively or intraoperatively developed surgical plan such that the cutting guide or jig will produce a precise bone cut in accordance with the surgical plan.

[0041] The Tracking System 115 uses one or more sensors to collect real-time position data that locates the patient's anatomy and surgical instruments. For example, for TKA procedures, the Tracking System may provide a location and orientation of the End Effector 105B during the procedure. In addition to positional data, data from the Tracking System 115 can also be used to infer velocity/acceleration of anatomy/instrumentation, which can be used for tool control. In some embodiments, the Tracking System 115 may use a tracker array attached to the End Effector 105B to determine the location and orientation of the End Effector 105B. The position of the End Effector 105B may be inferred based on the position and orientation of the Tracking System 115 and a known relationship in three-dimensional space between the Tracking System 115 and the End Effector 105B. Various types of tracking systems may be used in various embodiments of the present invention including, without limitation, Infrared (IR) tracking systems, electromagnetic (EM) tracking systems, video or image based tracking systems, and ultrasound registration and tracking systems. Using the data provided by the tracking system 115, the surgical computer 150 can detect objects and prevent collision. For example, the surgical computer 150 can prevent the Robotic Arm 105A and/or the End Effector 105B from colliding with soft tissue.

[0042] Any suitable tracking system can be used for tracking surgical objects and patient anatomy in the surgical theatre. For example, a combination of IR and visible light cameras can be used in an array. Various illumination sources, such as an IR LED light source, can illuminate the scene allowing three-dimensional imaging to occur. In some embodiments, this can include stereoscopic, tri-scopic, quad-scopic, etc. imaging. In addition to the camera array, which in some embodiments is affixed to a cart, additional cameras can be placed throughout the surgical theatre. For example, handheld tools or headsets worn by operators/surgeons can

include imaging capability that communicates images back to a central processor to correlate those images with images captured by the camera array. This can give a more robust image of the environment for modeling using multiple perspectives. Furthermore, some imaging devices may be of suitable resolution or have a suitable perspective on the scene to pick up information stored in quick response (QR) codes or barcodes. This can be helpful in identifying specific objects not manually registered with the system. In some embodiments, the camera may be mounted on the Robotic Arm 105A.

[0043] Although, as discussed herein, the majority of tracking and/or navigation techniques utilize image-based tracking systems (e.g., IR tracking systems, video or image based tracking systems, etc.). However, electromagnetic (EM) based tracking systems are becoming more common for a variety of reasons. For example, implantation of standard optical trackers requires tissue resection (e.g., down to the cortex) as well as subsequent drilling and driving of cortical pins. Additionally, because optical trackers require a direct line of sight with a tracking system, the placement of such trackers may need to be far from the surgical site to ensure they do not restrict the movement of a surgeon or medical professional.

[0044] Generally, EM based tracking devices include one or more wire coils and a reference field generator. The one or more wire coils may be energized (e.g., via a wired or wireless power supply). Once energized, the coil creates an electromagnetic field that can be detected and measured (e.g., by the reference field generator or an additional device) in a manner that allows for the location and orientation of the one or more wire coils to be determined. As should be understood by someone of ordinary skill in the art, a single coil, such as is shown in FIG. 2, is limited to detecting five (5) total degrees-of-freedom (DOF). For example, sensor 200 may be able to track/determine movement in the X, Y, or Z direction, as well as rotation around the Y-axis 202 or Z-axis 201. However, because of the electromagnetic properties of a coil, it is not possible to properly track rotational movement around the X axis.

[0045] Accordingly, in most electromagnetic tracking applications, a three coil system, such as that shown in FIG. 3A is used to enable tracking in all six degrees of freedom that are possible for a rigid body moving in a three-dimensional space (i.e., forward/backward 310, up/down 320, left/right 330, roll 340, pitch 350, and yaw 360). However, the inclusion of two additional coils and the 90° offset angles at which they are positioned may require the tracking device to be much larger. Alternatively, as one of skill in the art would know, less than three full coils may be

used to track all 6DOF. In some EM based tracking devices, two coils may be affixed to each other, such as is shown in FIG. 3B. Because the two coils 301B and 302B are rigidly affixed to each other, not perfectly parallel, and have locations that are known relative to each other, it is possible to determine the sixth degree of freedom 303B with this arrangement.

[0046] Although the use of two affixed coils (e.g., 301B and 302B) allows for EM based tracking in 6DOF, the sensor device is substantially larger in diameter than a single coil because of the additional coil. Thus, the practical application of using an EM based tracking system in a surgical environment may require tissue resection and drilling of a portion of the patient bone to allow for insertion of a EM tracker. Alternatively, in some embodiments, it may be possible to implant/insert a single coil, or 5DOF EM tracking device, into a patient bone using only a pin (e.g., without the need to drill or carve out substantial bone).

[0047] Thus, as described herein, a solution is needed for which the use of an EM tracking system can be restricted to devices small enough to be inserted/embedded using a small diameter needle or pin (i.e., without the need to create a new incision or large diameter opening in the bone). Accordingly, in some embodiments, a second 5DOF sensor, which is not attached to the first, and thus has a small diameter, may be used to track all 6DOF. Referring now to FIG. 3C, in some embodiments, two 5DOF EM sensors (e.g., 301C and 302C) may be inserted into the patient (e.g., in a patient bone) at different locations and with different angular orientations (e.g., angle 303C is non-zero).

[0048] Referring now to FIG. 4, an example embodiment is shown in which a first 5DOF EM sensor 401 and a second 5DOF EM sensor 402 are inserted into the patient bone 403 using a standard hollow needle 405 that is typical in most OR(s). In a further embodiment, the first sensor 401 and the second sensor 402 may have an angle offset of "α" 404. In some embodiments, it may be necessary for the offset angle "α" 404 to be greater than a predetermined value (e.g., a minimum angle of 0.50°, 0.75°, etc.). This minimum value may, in some embodiments, be determined by the CASS and provided to the surgeon or medical professional during the surgical plan. In some embodiments, a minimum value may be based on one or more factors, such as, for example, the orientation accuracy of the tracking system, a distance between the first and second EM sensors. The location of the field generator, a location of the field detector, a type of EM sensor, a quality of the EM sensor, patient anatomy, and the like.

[0049] Accordingly, as discussed herein, in some embodiments, a pin/needle (e.g., a cannulated mounting needle, etc.) may be used to insert one or more EM sensors. Generally, the pin/needle would be a disposable component, while the sensors themselves may be reusable. However, it should be understood that this is only one potential system, and that various other systems may be used in which the pin/needle and/or EM sensors are independently disposable or reusable. In a further embodiment, the EM sensors may be affixed to the mounting needle/pin (e.g., using a luer-lock fitting or the like), which can allow for quick assembly and disassembly. In additional embodiments, the EM sensors may utilize an alternative sleeve and/or anchor system that allows for minimally invasive placement of the sensors.

[0050] In another embodiment, the above systems may allow for a multi-sensor navigation system that can detect and correct for field distortions that plague electromagnetic tracking systems. It should be understood that field distortions may result from movement of any ferromagnetic materials within the reference field. Thus, as one of ordinary skill in the art would know, a typical OR has a large number of devices (e.g., an operating table, LCD displays, lighting equipment, imaging systems, surgical instruments, etc.) that may cause interference. Furthermore, field distortions are notoriously difficult to detect. The use of multiple EM sensors enables the system to detect field distortions accurately, and/or to warn a user that the current position measurements may not be accurate. Because the sensors are rigidly fixed to the bony anatomy (e.g., via the pin/needle), relative measurement of sensor positions (X, Y, Z) may be used to detect field distortions. By way of non-limiting example, in some embodiments, after the EM sensors are fixed to the bone, the relative distance between the two sensors is known and should remain constant. Thus, any change in this distance could indicate the presence of a field distortion.

[0051] In some embodiments, specific objects can be manually registered by a surgeon with the system preoperatively or intraoperatively. For example, by interacting with a user interface, a surgeon may identify the starting location for a tool or a bone structure. By tracking fiducial marks associated with that tool or bone structure, or by using other conventional image tracking modalities, a processor may track that tool or bone as it moves through the environment in a three-dimensional model.

[0052] In some embodiments, certain markers, such as fiducial marks that identify individuals, important tools, or bones in the theater may include passive or active identifiers that

can be picked up by a camera or camera array associated with the tracking system. For example, an IR LED can flash a pattern that conveys a unique identifier to the source of that pattern, providing a dynamic identification mark. Similarly, one or two dimensional optical codes (barcode, QR code, etc.) can be affixed to objects in the theater to provide passive identification that can occur based on image analysis. If these codes are placed asymmetrically on an object, they can also be used to determine an orientation of an object by comparing the location of the identifier with the extents of an object in an image. For example, a QR code may be placed in a corner of a tool tray, allowing the orientation and identity of that tray to be tracked. Other tracking modalities are explained throughout. For example, in some embodiments, augmented reality headsets can be worn by surgeons and other staff to provide additional camera angles and tracking capabilities.

[0053] In addition to optical tracking, certain features of objects can be tracked by registering physical properties of the object and associating them with objects that can be tracked, such as fiducial marks fixed to a tool or bone. For example, a surgeon may perform a manual registration process whereby a tracked tool and a tracked bone can be manipulated relative to one another. By impinging the tip of the tool against the surface of the bone, a three-dimensional surface can be mapped for that bone that is associated with a position and orientation relative to the frame of reference of that fiducial mark. By optically tracking the position and orientation (pose) of the fiducial mark associated with that bone, a model of that surface can be tracked with an environment through extrapolation.

[0054] The registration process that registers the CASS 100 to the relevant anatomy of the patient can also involve the use of anatomical landmarks, such as landmarks on a bone or cartilage. For example, the CASS 100 can include a 3D model of the relevant bone or joint and the surgeon can intraoperatively collect data regarding the location of bony landmarks on the patient's actual bone using a probe that is connected to the CASS. Bony landmarks can include, for example, the medial malleolus and lateral malleolus, the ends of the proximal femur and distal tibia, and the center of the hip joint. The CASS 100 can compare and register the location data of bony landmarks collected by the surgeon with the probe with the location data of the same landmarks in the 3D model. Alternatively, the CASS 100 can construct a 3D model of the bone or joint without pre-operative image data by using location data of bony landmarks and the bone surface that are collected by the surgeon using a CASS probe or other means. The

registration process can also include determining various axes of a joint. For example, for a TKA the surgeon can use the CASS 100 to determine the anatomical and mechanical axes of the femur and tibia. The surgeon and the CASS 100 can identify the center of the hip joint by moving the patient's leg in a spiral direction (i.e., circumduction) so the CASS can determine where the center of the hip joint is located.

[0055] A Tissue Navigation System 120 (not shown in FIG. 1) provides the surgeon with intraoperative, real-time visualization for the patient's bone, cartilage, muscle, nervous, and/or vascular tissues surrounding the surgical area. Examples of systems that may be employed for tissue navigation include fluorescent imaging systems and ultrasound systems.

[0056] The Display 125 provides graphical user interfaces (GUIs) that display images collected by the Tissue Navigation System 120 as well other information relevant to the surgery. For example, in one embodiment, the Display 125 overlays image information collected from various modalities (e.g., CT, MRI, X-ray, fluorescent, ultrasound, etc.) collected pre-operatively or intraoperatively to give the surgeon various views of the patient's anatomy as well as real-time conditions. The Display 125 may include, for example, one or more computer monitors. As an alternative or supplement to the Display 125, one or more members of the surgical staff may wear an Augmented Reality (AR) Head Mounted Device (HMD). For example, in FIG. 1 the Surgeon 111 is wearing an AR HMD 155 that may, for example, overlay pre-operative image data on the patient or provide surgical planning suggestions. Various example uses of the AR HMD 155 in surgical procedures are detailed in the sections that follow.

[0057] Surgical Computer 150 provides control instructions to various components of the CASS 100, collects data from those components, and provides general processing for various data needed during surgery. In some embodiments, the Surgical Computer 150 is a general purpose computer. In other embodiments, the Surgical Computer 150 may be a parallel computing platform that uses multiple central processing units (CPUs) or graphics processing units (GPU) to perform processing. In some embodiments, the Surgical Computer 150 is connected to a remote server over one or more computer networks (e.g., the Internet). The remote server can be used, for example, for storage of data or execution of computationally intensive processing tasks.

[0058] Various techniques generally known in the art can be used for connecting the Surgical Computer 150 to the other components of the CASS 100. Moreover, the computers can connect

to the Surgical Computer 150 using a mix of technologies. For example, the End Effector 105B may connect to the Surgical Computer 150 over a wired (i.e., serial) connection. The Tracking System 115, Tissue Navigation System 120, and Display 125 can similarly be connected to the Surgical Computer 150 using wired connections. Alternatively, the Tracking System 115, Tissue Navigation System 120, and Display 125 may connect to the Surgical Computer 150 using wireless technologies such as, without limitation, Wi-Fi, Bluetooth, Near Field Communication (NFC), or ZigBee.

[0059] Powered Impaction and Acetabular Reamer Devices

[0060] Part of the flexibility of the CASS design described above with respect to FIG. 1 is that additional or alternative devices can be added to the CASS 100 as necessary to support particular surgical procedures. For example, in the context of hip surgeries, the CASS 100 may include a powered impaction device. Impaction devices are designed to repeatedly apply an impaction force that the surgeon can use to perform activities such as implant alignment. For example, within a total hip arthroplasty (THA), a surgeon will often insert a prosthetic acetabular cup into the implant host's acetabulum using an impaction device. Although impaction devices can be manual in nature (e.g., operated by the surgeon striking an impactor with a mallet), powered impaction devices are generally easier and quicker to use in the surgical setting. Powered impaction devices may be powered, for example, using a battery attached to the device. Various attachment pieces may be connected to the powered impaction device to allow the impaction force to be directed in various ways as needed during surgery. Also in the context of hip surgeries, the CASS 100 may include a powered, robotically controlled end effector to ream the acetabulum to accommodate an acetabular cup implant.

[0061] In a robotically-assisted THA, the patient's anatomy can be registered to the CASS 100 using CT or other image data, the identification of anatomical landmarks, tracker arrays attached to the patient's bones, and one or more cameras. Tracker arrays can be mounted on the iliac crest using clamps and/or bone pins and such trackers can be mounted externally through the skin or internally (either posterolaterally or anterolaterally) through the incision made to perform the THA. For a THA, the CASS 100 can utilize one or more femoral cortical screws inserted into the proximal femur as checkpoints to aid in the registration process. The CASS 100 can also utilize one or more checkpoint screws inserted into the pelvis as additional checkpoints to aid in the registration process. Femoral tracker arrays can be secured to or mounted in the

femoral cortical screws. The CASS 100 can employ steps where the registration is verified using a probe that the surgeon precisely places on key areas of the proximal femur and pelvis identified for the surgeon on the display 125. Trackers can be located on the robotic arm 105A or end effector 105B to register the arm and/or end effector to the CASS 100. The verification step can also utilize proximal and distal femoral checkpoints. The CASS 100 can utilize color prompts or other prompts to inform the surgeon that the registration process for the relevant bones and the robotic arm 105A or end effector 105B has been verified to a certain degree of accuracy (e.g., within 1mm).

[0062] For a THA, the CASS 100 can include a broach tracking option using femoral arrays to allow the surgeon to intraoperatively capture the broach position and orientation and calculate hip length and offset values for the patient. Based on information provided about the patient's hip joint and the planned implant position and orientation after broach tracking is completed, the surgeon can make modifications or adjustments to the surgical plan.

[0063] For a robotically-assisted THA, the CASS 100 can include one or more powered reamers connected or attached to a robotic arm 105A or end effector 105B that prepares the pelvic bone to receive an acetabular implant according to a surgical plan. The robotic arm 105A and/or end effector 105B can inform the surgeon and/or control the power of the reamer to ensure that the acetabulum is being resected (reamed) in accordance with the surgical plan. For example, if the surgeon attempts to resect bone outside of the boundary of the bone to be resected in accordance with the surgical plan, the CASS 100 can power off the reamer or instruct the surgeon to power off the reamer. The CASS 100 can provide the surgeon with an option to turn off or disengage the robotic control of the reamer. The display 125 can depict the progress of the bone being resected (reamed) as compared to the surgical plan using different colors. The surgeon can view the display of the bone being resected (reamed) to guide the reamer to complete the reaming in accordance with the surgical plan. The CASS 100 can provide visual or audible prompts to the surgeon to warn the surgeon that resections are being made that are not in accordance with the surgical plan.

[0064] Following reaming, the CASS 100 can employ a manual or powered impactor that is attached or connected to the robotic arm 105A or end effector 105B to impact trial implants and final implants into the acetabulum. The robotic arm 105A and/or end effector 105B can be used to guide the impactor to impact the trial and final implants into the acetabulum in accordance

with the surgical plan. The CASS 100 can cause the position and orientation of the trial and final implants vis-à-vis the bone to be displayed to inform the surgeon as to how the trial and final implant's orientation and position compare to the surgical plan, and the display 125 can show the implant's position and orientation as the surgeon manipulates the leg and hip. The CASS 100 can provide the surgeon with the option of re-planning and re-doing the reaming and implant impaction by preparing a new surgical plan if the surgeon is not satisfied with the original implant position and orientation.

[0065] Preoperatively, the CASS 100 can develop a proposed surgical plan based on a three dimensional model of the hip joint and other information specific to the patient, such as the mechanical and anatomical axes of the leg bones, the epicondylar axis, the femoral neck axis, the dimensions (e.g., length) of the femur and hip, the midline axis of the hip joint, the ASIS axis of the hip joint, and the location of anatomical landmarks such as the lesser trochanter landmarks, the distal landmark, and the center of rotation of the hip joint. The CASS-developed surgical plan can provide a recommended optimal implant size and implant position and orientation based on the three dimensional model of the hip joint and other information specific to the patient. The CASS-developed surgical plan can include proposed details on offset values, inclination and anteversion values, center of rotation, cup size, medialization values, superior-inferior fit values, femoral stem sizing and length.

[0066] For a THA, the CASS-developed surgical plan can be viewed preoperatively and intraoperatively, and the surgeon can modify CASS-developed surgical plan preoperatively or intraoperatively. The CASS-developed surgical plan can display the planned resection to the hip joint and superimpose the planned implants onto the hip joint based on the planned resections. The CASS 100 can provide the surgeon with options for different surgical workflows that will be displayed to the surgeon based on a surgeon's preference. For example, the surgeon can choose from different workflows based on the number and types of anatomical landmarks that are checked and captured and/or the location and number of tracker arrays used in the registration process.

[0067] According to some embodiments, a powered impaction device used with the CASS 100 may operate with a variety of different settings. In some embodiments, the surgeon adjusts settings through a manual switch or other physical mechanism on the powered impaction device. In other embodiments, a digital interface may be used that allows setting entry, for example, via

a touchscreen on the powered impaction device. Such a digital interface may allow the available settings to vary based, for example, on the type of attachment piece connected to the power attachment device. In some embodiments, rather than adjusting the settings on the powered impaction device itself, the settings can be changed through communication with a robot or other computer system within the CASS 100. Such connections may be established using, for example, a Bluetooth or Wi-Fi networking module on the powered impaction device. In another embodiment, the impaction device and end pieces may contain features that allow the impaction device to be aware of what end piece (cup impactor, broach handle, etc.) is attached with no action required by the surgeon, and adjust the settings accordingly. This may be achieved, for example, through a QR code, barcode, RFID tag, or other method.

[0068] Examples of the settings that may be used include cup impaction settings (e.g., single direction, specified frequency range, specified force and/or energy range); broach impaction settings (e.g., dual direction/oscillating at a specified frequency range, specified force and/or energy range); femoral head impaction settings (e.g., single direction/single blow at a specified force or energy); and stem impaction settings (e.g., single direction at specified frequency with a specified force or energy). Additionally, in some embodiments, the powered impaction device includes settings related to acetabular liner impaction (e.g., single direction/single blow at a specified force or energy). There may be a plurality of settings for each type of liner such as poly, ceramic, oxinium, or other materials. Furthermore, the powered impaction device may offer settings for different bone quality based on preoperative testing/imaging/knowledge and/or intraoperative assessment by surgeon. In some embodiments, the powered impactor device may have a dual function. For example, the powered impactor device not only could provide reciprocating motion to provide an impact force, but also could provide reciprocating motion for a broach or rasp.

[0069] In some embodiments, the powered impaction device includes feedback sensors that gather data during instrument use, and send data to a computing device such as a controller within the device or the Surgical Computer 150. This computing device can then record the data for later analysis and use. Examples of the data that may be collected include, without limitation, sound waves, the predetermined resonance frequency of each instrument, reaction force or rebound energy from patient bone, location of the device with respect to imaging (e.g.,

fluoro, CT, ultrasound, MRI, etc.) registered bony anatomy, and/or external strain gauges on bones.

[0070] Once the data is collected, the computing device may execute one or more algorithms in real-time or near real-time to aid the surgeon in performing the surgical procedure. For example, in some embodiments, the computing device uses the collected data to derive information such as the proper final broach size (femur); when the stem is fully seated (femur side); or when the cup is seated (depth and/or orientation) for a THA. Once the information is known, it may be displayed for the surgeon's review, or it may be used to activate haptics or other feedback mechanisms to guide the surgical procedure.

[0071] Additionally, the data derived from the aforementioned algorithms may be used to drive operation of the device. For example, during insertion of a prosthetic acetabular cup with a powered impaction device, the device may automatically extend an impaction head (e.g., an end effector) moving the implant into the proper location, or turn the power off to the device once the implant is fully seated. In one embodiment, the derived information may be used to automatically adjust settings for quality of bone where the powered impaction device should use less power to mitigate femoral/acetabular/pelvic fracture or damage to surrounding tissues.

[0072] Robotic arm

[0073] In some embodiments, the CASS 100 includes a robotic arm 105A that serves as an interface to stabilize and hold a variety of instruments used during the surgical procedure. For example, in the context of a hip surgery, these instruments may include, without limitation, retractors, a sagittal or reciprocating saw, the reamer handle, the cup impactor, the broach handle, and the stem inserter. The robotic arm 105A may have multiple degrees of freedom (like a Spider device), and have the ability to be locked in place (e.g., by a press of a button, voice activation, a surgeon removing a hand from the robotic arm, or other method).

[0074] In some embodiments, movement of the robotic arm 105A may be effectuated by use of a control panel built into the robotic arm system. For example, a display screen may include one or more input sources, such as physical buttons or a user interface having one or more icons, that direct movement of the robotic arm 105A. The surgeon or other healthcare professional may engage with the one or more input sources to position the robotic arm 105A when performing a surgical procedure.

[0075] A tool or an end effector 105B attached or integrated into a robotic arm 105A may include, without limitation, a burring device, a scalpel, a cutting device, a retractor, a joint tensioning device, or the like. In embodiments in which an end effector 105B is used, the end effector may be positioned at the end of the robotic arm 105A such that any motor control operations are performed within the robotic arm system. In embodiments in which a tool is used, the tool may be secured at a distal end of the robotic arm 105A, but motor control operation may reside within the tool itself.

[0076] The robotic arm 105A may be motorized internally to both stabilize the robotic arm, thereby preventing it from falling and hitting the patient, surgical table, surgical staff, etc., and to allow the surgeon to move the robotic arm without having to fully support its weight. While the surgeon is moving the robotic arm 105A, the robotic arm may provide some resistance to prevent the robotic arm from moving too fast or having too many degrees of freedom active at once. The position and the lock status of the robotic arm 105A may be tracked, for example, by a controller or the Surgical Computer 150.

[0077] In some embodiments, the robotic arm 105A can be moved by hand (e.g., by the surgeon) or with internal motors into its ideal position and orientation for the task being performed. In some embodiments, the robotic arm 105A may be enabled to operate in a "free" mode that allows the surgeon to position the arm into a desired position without being restricted. While in the free mode, the position and orientation of the robotic arm 105A may still be tracked as described above. In one embodiment, certain degrees of freedom can be selectively released upon input from user (e.g., surgeon) during specified portions of the surgical plan tracked by the Surgical Computer 150. Designs in which a robotic arm 105A is internally powered through hydraulics or motors or provides resistance to external manual motion through similar means can be described as powered robotic arms, while arms that are manually manipulated without power feedback, but which may be manually or automatically locked in place, may be described as passive robotic arms.

[0078] A robotic arm 105A or end effector 105B can include a trigger or other means to control the power of a saw or drill. Engagement of the trigger or other means by the surgeon can cause the robotic arm 105A or end effector 105B to transition from a motorized alignment mode to a mode where the saw or drill is engaged and powered on. Additionally, the CASS 100 can include a foot pedal (not shown) that causes the system to perform certain functions when

activated. For example, the surgeon can activate the foot pedal to instruct the CASS 100 to place the robotic arm 105A or end effector 105B in an automatic mode that brings the robotic arm or end effector into the proper position with respect to the patient's anatomy in order to perform the necessary resections. The CASS 100 can also place the robotic arm 105A or end effector 105B in a collaborative mode that allows the surgeon to manually manipulate and position the robotic arm or end effector into a particular location. The collaborative mode can be configured to allow the surgeon to move the robotic arm 105A or end effector 105B medially or laterally, while restricting movement in other directions. As discussed, the robotic arm 105A or end effector 105B can include a cutting device (saw, drill, and burr) or a cutting guide or jig 105D that will guide a cutting device. In other embodiments, movement of the robotic arm 105A or robotically controlled end effector 105B can be controlled entirely by the CASS 100 without any, or with only minimal, assistance or input from a surgeon or other medical professional. In still other embodiments, the movement of the robotic arm 105A or robotically controlled end effector 105B can be controlled remotely by a surgeon or other medical professional using a control mechanism separate from the robotic arm or robotically controlled end effector device, for example using a joystick or interactive monitor or display control device.

[0079] The examples below describe uses of the robotic device in the context of a hip surgery; however, it should be understood that the robotic arm may have other applications for surgical procedures involving knees, shoulders, etc. One example of use of a robotic arm in the context of forming an anterior cruciate ligament (ACL) graft tunnel is described in WIPO Publication No. WO 2020/047051 filed August 28, 2019 and entitled "Robotic Assisted Ligament Graft Placement and Tensioning," the entirety of which is incorporated herein by reference.

[0080] A robotic arm 105A may be used for holding the retractor. For example in one embodiment, the robotic arm 105A may be moved into the desired position by the surgeon. At that point, the robotic arm 105A may lock into place. In some embodiments, the robotic arm 105A is provided with data regarding the patient's position, such that if the patient moves, the robotic arm can adjust the retractor position accordingly. In some embodiments, multiple robotic arms may be used, thereby allowing multiple retractors to be held or for more than one activity to be performed simultaneously (e.g., retractor holding & reaming).

[0081] The robotic arm 105A may also be used to help stabilize the surgeon's hand while making a femoral neck cut. In this application, control of the robotic arm 105A may impose certain restrictions to prevent soft tissue damage from occurring. For example, in one embodiment, the Surgical Computer 150 tracks the position of the robotic arm 105A as it operates. If the tracked location approaches an area where tissue damage is predicted, a command may be sent to the robotic arm 105A causing it to stop. Alternatively, where the robotic arm 105A is automatically controlled by the Surgical Computer 150, the Surgical Computer may ensure that the robotic arm is not provided with any instructions that cause it to enter areas where soft tissue damage is likely to occur. The Surgical Computer 150 may impose certain restrictions on the surgeon to prevent the surgeon from reaming too far into the medial wall of the acetabulum or reaming at an incorrect angle or orientation.

[0082] In some embodiments, the robotic arm 105A may be used to hold a cup impactor at a desired angle or orientation during cup impaction. When the final position has been achieved, the robotic arm 105A may prevent any further seating to prevent damage to the pelvis.

[0083] The surgeon may use the robotic arm 105A to position the broach handle at the desired position and allow the surgeon to impact the broach into the femoral canal at the desired orientation. In some embodiments, once the Surgical Computer 150 receives feedback that the broach is fully seated, the robotic arm 105A may restrict the handle to prevent further advancement of the broach.

[0084] The robotic arm 105A may also be used for resurfacing applications. For example, the robotic arm 105A may stabilize the surgeon while using traditional instrumentation and provide certain restrictions or limitations to allow for proper placement of implant components (e.g., guide wire placement, chamfer cutter, sleeve cutter, plan cutter, etc.). Where only a burr is employed, the robotic arm 105A may stabilize the surgeon's handpiece and may impose restrictions on the handpiece to prevent the surgeon from removing unintended bone in contravention of the surgical plan.

[0085] The robotic arm 105A may be a passive arm. As an example, the robotic arm 105A may be a CIRQ robot arm available from Brainlab AG. CIRQ is a registered trademark of Brainlab AG, Olof-Palme-Str. 9 81829, München, FED REP of GERMANY. In one particular embodiment, the robotic arm 105A is an intelligent holding arm as disclosed in U.S. Patent Application No. 15/525,585 to Krinninger et al., U.S. Patent Application No. 15/561,042 to

Nowatschin et al., U.S. Patent Application No. 15/561,048 to Nowatschin et al., and U.S. Patent No. 10,342,636 to Nowatschin et al., the entire contents of each of which is herein incorporated by reference.

[0086] Surgical Procedure Data Generation and Collection

[0087] The various services that are provided by medical professionals to treat a clinical condition are collectively referred to as an "episode of care." For a particular surgical intervention the episode of care can include three phases: pre-operative, intraoperative, and post-operative. During each phase, data is collected or generated that can be used to analyze the episode of care in order to understand various features of the procedure and identify patterns that may be used, for example, in training models to make decisions with minimal human intervention. The data collected over the episode of care may be stored at the Surgical Computer 150 or the Surgical Data Server 180 as a complete dataset. Thus, for each episode of care, a dataset exists that comprises all of the data collectively pre-operatively about the patient, all of the data collected or stored by the CASS 100 intraoperatively, and any post-operative data provided by the patient or by a healthcare professional monitoring the patient.

[0088] As explained in further detail, the data collected during the episode of care may be used to enhance performance of the surgical procedure or to provide a holistic understanding of the surgical procedure and the patient outcomes. For example, in some embodiments, the data collected over the episode of care may be used to generate a surgical plan. In one embodiment, a high-level, pre-operative plan is refined intraoperatively as data is collected during surgery. In this way, the surgical plan can be viewed as dynamically changing in real-time or near real-time as new data is collected by the components of the CASS 100. In other embodiments, pre-operative images or other input data may be used to develop a robust plan preoperatively that is simply executed during surgery. In this case, the data collected by the CASS 100 during surgery may be used to make recommendations that ensure that the surgeon stays within the pre-operative surgical plan. For example, if the surgeon is unsure how to achieve a certain prescribed cut or implant alignment, the Surgical Computer 150 can be queried for a recommendation. In still other embodiments, the pre-operative and intraoperative planning approaches can be combined such that a robust pre-operative plan can be dynamically modified, as necessary or desired, during the surgical procedure. In some embodiments, a biomechanics-based model of patient anatomy contributes simulation data to be considered by the CASS 100 in

developing preoperative, intraoperative, and post-operative/rehabilitation procedures to optimize implant performance outcomes for the patient.

[0089] Aside from changing the surgical procedure itself, the data gathered during the episode of care may be used as an input to other procedures ancillary to the surgery. For example, in some embodiments, implants can be designed using episode of care data. Example data-driven techniques for designing, sizing, and fitting implants are described in U.S. Patent Application No. 13/814,531 filed August 15, 2011 and entitled "Systems and Methods for Optimizing Parameters for Orthopaedic Procedures"; U.S. Patent Application No. 14/232,958 filed July 20, 2012 and entitled "Systems and Methods for Optimizing Fit of an Implant to Anatomy"; and U.S. Patent Application No. 12/234,444 filed September 19, 2008 and entitled "Operatively Tuning Implants for Increased Performance," the entire contents of each of which are hereby incorporated by reference into this patent application.

[0090] Furthermore, the data can be used for educational, training, or research purposes. For example, using the network-based approach described below in FIG. 5C, other doctors or students can remotely view surgeries in interfaces that allow them to selectively view data as it is collected from the various components of the CASS 100. After the surgical procedure, similar interfaces may be used to "playback" a surgery for training or other educational purposes, or to identify the source of any issues or complications with the procedure.

[0091] Data acquired during the pre-operative phase generally includes all information collected or generated prior to the surgery. Thus, for example, information about the patient may be acquired from a patient intake form or electronic medical record (EMR). Examples of patient information that may be collected include, without limitation, patient demographics, diagnoses, medical histories, progress notes, vital signs, medical history information, allergies, and lab results. The pre-operative data may also include images related to the anatomical area of interest. These images may be captured, for example, using Magnetic Resonance Imaging (MRI), Computed Tomography (CT), X-ray, ultrasound, or any other modality known in the art. The pre-operative data may also comprise quality of life data captured from the patient. For example, in one embodiment, pre-surgery patients use a mobile application ("app") to answer questionnaires regarding their current quality of life. In some embodiments, preoperative data used by the CASS 100 includes demographic, anthropometric, cultural, or other specific traits about a patient that can coincide with activity levels and specific patient activities to customize

the surgical plan to the patient. For example, certain cultures or demographics may be more likely to use a toilet that requires squatting on a daily basis.

[0092] FIGS. 5A and 5B provide examples of data that may be acquired during the intraoperative phase of an episode of care. These examples are based on the various components of the CASS 100 described above with reference to FIG. 1; however, it should be understood that other types of data may be used based on the types of equipment used during surgery and their use.

[0093] FIG. 5A shows examples of some of the control instructions that the Surgical Computer 150 provides to other components of the CASS 100, according to some embodiments. Note that the example of FIG. 5A assumes that the components of the Effector Platform 105 are each controlled directly by the Surgical Computer 150. In embodiments where a component is manually controlled by the Surgeon 111, instructions may be provided on the Display 125 or AR HMD 155 instructing the Surgeon 111 how to move the component.

[0094] The various components included in the Effector Platform 105 are controlled by the Surgical Computer 150 providing position commands that instruct the component where to move within a coordinate system. In some embodiments, the Surgical Computer 150 provides the Effector Platform 105 with instructions defining how to react when a component of the Effector Platform 105 deviates from a surgical plan. These commands are referenced in FIG. 5A as "haptic" commands. For example, the End Effector 105B may provide a force to resist movement outside of an area where resection is planned. Other commands that may be used by the Effector Platform 105 include vibration and audio cues.

[0095] In some embodiments, the end effectors 105B of the robotic arm 105A are operatively coupled with cutting guide 105D. In response to an anatomical model of the surgical scene, the robotic arm 105A can move the end effectors 105B and the cutting guide 105D into position to match the location of the femoral or tibial cut to be performed in accordance with the surgical plan. This can reduce the likelihood of error, allowing the vision system and a processor utilizing that vision system to implement the surgical plan to place a cutting guide 105D at the precise location and orientation relative to the tibia or femur to align a cutting slot of the cutting guide with the cut to be performed according to the surgical plan. Then, a surgeon can use any suitable tool, such as an oscillating or rotating saw or drill to perform the cut (or drill a hole) with perfect placement and orientation because the tool is mechanically limited by the features of the

cutting guide 105D. In some embodiments, the cutting guide 105D may include one or more pin holes that are used by a surgeon to drill and screw or pin the cutting guide into place before performing a resection of the patient tissue using the cutting guide. This can free the robotic arm 105A or ensure that the cutting guide 105D is fully affixed without moving relative to the bone to be resected. For example, this procedure can be used to make the first distal cut of the femur during a total knee arthroplasty. In some embodiments, where the arthroplasty is a hip arthroplasty, cutting guide 105D can be fixed to the femoral head or the acetabulum for the respective hip arthroplasty resection. It should be understood that any arthroplasty that utilizes precise cuts can use the robotic arm 105A and/or cutting guide 105D in this manner.

[0096] The Resection Equipment 110 is provided with a variety of commands to perform bone or tissue operations. As with the Effector Platform 105, position information may be provided to the Resection Equipment 110 to specify where it should be located when performing resection. Other commands provided to the Resection Equipment 110 may be dependent on the type of resection equipment. For example, for a mechanical or ultrasonic resection tool, the commands may specify the speed and frequency of the tool. For Radiofrequency Ablation (RFA) and other laser ablation tools, the commands may specify intensity and pulse duration.

[0097] Some components of the CASS 100 do not need to be directly controlled by the Surgical Computer 150; rather, the Surgical Computer 150 only needs to activate the component, which then executes software locally specifying the manner in which to collect data and provide it to the Surgical Computer 150. In the example of FIG. 2A, there are two components that are operated in this manner: the Tracking System 115 and the Tissue Navigation System 120.

[0098] The Surgical Computer 150 provides the Display 125 with any visualization that is needed by the Surgeon 111 during surgery. For monitors, the Surgical Computer 150 may provide instructions for displaying images, GUIs, etc. using techniques known in the art. The display 125 can include various portions of the workflow of a surgical plan. During the registration process, for example, the display 125 can show a preoperatively constructed 3D bone model and depict the locations of the probe as the surgeon uses the probe to collect locations of anatomical landmarks on the patient. The display 125 can include information about the surgical target area. For example, in connection with a TKA, the display 125 can depict the mechanical and anatomical axes of the femur and tibia. The display 125 can depict varus and valgus angles for the knee joint based on a surgical plan, and the CASS 100 can depict how such angles will be

affected if contemplated revisions to the surgical plan are made. Accordingly, the display 125 is an interactive interface that can dynamically update and display how changes to the surgical plan would impact the procedure and the final position and orientation of implants installed on bone.

[0099] As the workflow progresses to preparation of bone cuts or resections, the display 125 can depict the planned or recommended bone cuts before any cuts are performed. The surgeon 111 can manipulate the image display to provide different anatomical perspectives of the target area and can have the option to alter or revise the planned bone cuts based on intraoperative evaluation of the patient. The display 125 can depict how the chosen implants would be installed on the bone if the planned bone cuts are performed. If the surgeon 111 choses to change the previously planned bone cuts, the display 125 can depict how the revised bone cuts would change the position and orientation of the implant when installed on the bone.

[0100] The display 125 can provide the surgeon 111 with a variety of data and information about the patient, the planned surgical intervention, and the implants. Various patient-specific information can be displayed, including real-time data concerning the patient's health such as heart rate, blood pressure, etc. The display 125 can also include information about the anatomy of the surgical target region including the location of landmarks, the current state of the anatomy (e.g., whether any resections have been made, the depth and angles of planned and executed bone cuts), and future states of the anatomy as the surgical plan progresses. The display 125 can also provide or depict additional information about the surgical target region. For a TKA, the display 125 can provide information about the gaps (e.g., gap balancing) between the femur and tibia and how such gaps will change if the planned surgical plan is carried out. For a TKA, the display 125 can provide additional relevant information about the knee joint such as data about the joint's tension (e.g., ligament laxity) and information concerning rotation and alignment of the joint. The display 125 can depict how the planned implants' locations and positions will affect the patient as the knee joint is flexed. The display 125 can depict how the use of different implants or the use of different sizes of the same implant will affect the surgical plan and preview how such implants will be positioned on the bone. The CASS 100 can provide such information for each of the planned bone resections in a TKA or THA. In a TKA, the CASS 100 can provide robotic control for one or more of the planned bone resections. For example, the CASS 100 can provide robotic control only for the initial distal femur cut, and the surgeon 111

can manually perform other resections (anterior, posterior and chamfer cuts) using conventional means, such as a 4-in-1 cutting guide or jig 105D.

[0101] The display 125 can employ different colors to inform the surgeon of the status of the surgical plan. For example, un-resected bone can be displayed in a first color, resected bone can be displayed in a second color, and planned resections can be displayed in a third color. Implants can be superimposed onto the bone in the display 125, and implant colors can change or correspond to different types or sizes of implants.

[0102] The information and options depicted on the display 125 can vary depending on the type of surgical procedure being performed. Further, the surgeon 111 can request or select a particular surgical workflow display that matches or is consistent with his or her surgical plan preferences. For example, for a surgeon 111 who typically performs the tibial cuts before the femoral cuts in a TKA, the display 125 and associated workflow can be adapted to take this preference into account. The surgeon 111 can also preselect that certain steps be included or deleted from the standard surgical workflow display. For example, if a surgeon 111 uses resection measurements to finalize an implant plan but does not analyze ligament gap balancing when finalizing the implant plan, the surgical workflow display can be organized into modules, and the surgeon can select which modules to display and the order in which the modules are provided based on the surgeon's preferences or the circumstances of a particular surgery. Modules directed to ligament and gap balancing, for example, can include pre- and post-resection ligament/gap balancing, and the surgeon 111 can select which modules to include in their default surgical plan workflow depending on whether they perform such ligament and gap balancing before or after (or both) bone resections are performed.

[0103] For more specialized display equipment, such as AR HMDs, the Surgical Computer 150 may provide images, text, etc. using the data format supported by the equipment. For example, if the Display 125 is a holography device such as the Microsoft HoloLens™ or Magic Leap One™, the Surgical Computer 150 may use the HoloLens Application Program Interface (API) to send commands specifying the position and content of holograms displayed in the field of view of the Surgeon 111.

[0104] In some embodiments, one or more surgical planning models may be incorporated into the CASS 100 and used in the development of the surgical plans provided to the surgeon 111. The term "surgical planning model" refers to software that simulates the biomechanics

performance of anatomy under various scenarios to determine the optimal way to perform cutting and other surgical activities. For example, for knee replacement surgeries, the surgical planning model can measure parameters for functional activities, such as deep knee bends, gait, etc., and select cut locations on the knee to optimize implant placement. One example of a surgical planning model is the LIFEMOD™ simulation software from SMITH AND NEPHEW, INC. In some embodiments, the Surgical Computer 150 includes computing architecture that allows full execution of the surgical planning model during surgery (e.g., a GPU-based parallel processing environment). In other embodiments, the Surgical Computer 150 may be connected over a network to a remote computer that allows such execution, such as a Surgical Data Server 180 (see FIG. 5C). As an alternative to full execution of the surgical planning model, in some embodiments, a set of transfer functions are derived that simplify the mathematical operations captured by the model into one or more predictor equations. Then, rather than execute the full simulation during surgery, the predictor equations are used. Further details on the use of transfer functions are described in WIPO Publication No. 2020/037308, filed August 19, 2019, entitled "Patient Specific Surgical Method and System," the entirety of which is incorporated herein by reference.

[0105] FIG. 5B shows examples of some of the types of data that can be provided to the Surgical Computer 150 from the various components of the CASS 100. In some embodiments, the components may stream data to the Surgical Computer 150 in real-time or near real-time during surgery. In other embodiments, the components may queue data and send it to the Surgical Computer 150 at set intervals (e.g., every second). Data may be communicated using any format known in the art. Thus, in some embodiments, the components all transmit data to the Surgical Computer 150 in a common format. In other embodiments, each component may use a different data format, and the Surgical Computer 150 is configured with one or more software applications that enable translation of the data.

[0106] In general, the Surgical Computer 150 may serve as the central point where CASS data is collected. The exact content of the data will vary depending on the source. For example, each component of the Effector Platform 105 provides a measured position to the Surgical Computer 150. Thus, by comparing the measured position to a position originally specified by the Surgical Computer 150 (see FIG. 5B), the Surgical Computer can identify deviations that take place during surgery.

[0107] The Resection Equipment 110 can send various types of data to the Surgical Computer 150 depending on the type of equipment used. Example data types that may be sent include the measured torque, audio signatures, and measured displacement values. Similarly, the Tracking Technology 115 can provide different types of data depending on the tracking methodology employed. Example tracking data types include position values for tracked items (e.g., anatomy, tools, etc.), ultrasound images, and surface or landmark collection points or axes. The Tissue Navigation System 120 provides the Surgical Computer 150 with anatomic locations, shapes, etc. as the system operates.

[0108] Although the Display 125 generally is used for outputting data for presentation to the user, it may also provide data to the Surgical Computer 150. For example, for embodiments where a monitor is used as part of the Display 125, the Surgeon 111 may interact with a GUI to provide inputs which are sent to the Surgical Computer 150 for further processing. For AR applications, the measured position and displacement of the HMD may be sent to the Surgical Computer 150 so that it can update the presented view as needed.

[0109] During the post-operative phase of the episode of care, various types of data can be collected to quantify the overall improvement or deterioration in the patient's condition as a result of the surgery. The data can take the form of, for example, self-reported information reported by patients via questionnaires. For example, in the context of a knee replacement surgery, functional status can be measured with an Oxford Knee Score questionnaire, and the post-operative quality of life can be measured with a EQ5D-5L questionnaire. Other examples in the context of a hip replacement surgery may include the Oxford Hip Score, Harris Hip Score, and WOMAC (Western Ontario and McMaster Universities Osteoarthritis index). Such questionnaires can be administered, for example, by a healthcare professional directly in a clinical setting or using a mobile app that allows the patient to respond to questions directly. In some embodiments, the patient may be outfitted with one or more wearable devices that collect data relevant to the surgery. For example, following a knee surgery, the patient may be outfitted with a knee brace that includes sensors that monitor knee positioning, flexibility, etc. This information can be collected and transferred to the patient's mobile device for review by the surgeon to evaluate the outcome of the surgery and address any issues. In some embodiments, one or more cameras can capture and record the motion of a patient's body segments during specified activities postoperatively. This motion capture can be compared to a biomechanics

model to better understand the functionality of the patient's joints and better predict progress in recovery and identify any possible revisions that may be needed.

[0110] The post-operative stage of the episode of care can continue over the entire life of a patient. For example, in some embodiments, the Surgical Computer 150 or other components comprising the CASS 100 can continue to receive and collect data relevant to a surgical procedure after the procedure has been performed. This data may include, for example, images, answers to questions, "normal" patient data (e.g., blood type, blood pressure, conditions, medications, etc.), biometric data (e.g., gait, etc.), and objective and subjective data about specific issues (e.g., knee or hip joint pain). This data may be explicitly provided to the Surgical Computer 150 or other CASS component by the patient or the patient's physician(s). Alternatively or additionally, the Surgical Computer 150 or other CASS component can monitor the patient's EMR and retrieve relevant information as it becomes available. This longitudinal view of the patient's recovery allows the Surgical Computer 150 or other CASS component to provide a more objective analysis of the patient's outcome to measure and track success or lack of success for a given procedure. For example, a condition experienced by a patient long after the surgical procedure can be linked back to the surgery through a regression analysis of various data items collected during the episode of care. This analysis can be further enhanced by performing the analysis on groups of patients that had similar procedures and/or have similar anatomies.

[0111] In some embodiments, data is collected at a central location to provide for easier analysis and use. Data can be manually collected from various CASS components in some instances. For example, a portable storage device (e.g., USB stick) can be attached to the Surgical Computer 150 into order to retrieve data collected during surgery. The data can then be transferred, for example, via a desktop computer to the centralized storage. Alternatively, in some embodiments, the Surgical Computer 150 is connected directly to the centralized storage via a Network 175 as shown in FIG. 5C.

[0112] FIG. 5C illustrates a "cloud-based" implementation in which the Surgical Computer 150 is connected to a Surgical Data Server 180 via a Network 175. This Network 175 may be, for example, a private intranet or the Internet. In addition to the data from the Surgical Computer 150, other sources can transfer relevant data to the Surgical Data Server 180. The example of FIG. 5C shows 3 additional data sources: the Patient 160, Healthcare Professional(s)

165, and an EMR Database 170. Thus, the Patient 160 can send pre-operative and post-operative data to the Surgical Data Server 180, for example, using a mobile app. The Healthcare Professional(s) 165 includes the surgeon and his or her staff as well as any other professionals working with Patient 160 (e.g., a personal physician, a rehabilitation specialist, etc.). It should also be noted that the EMR Database 170 may be used for both pre-operative and post-operative data. For example, assuming that the Patient 160 has given adequate permissions, the Surgical Data Server 180 may collect the EMR of the Patient pre-surgery. Then, the Surgical Data Server 180 may continue to monitor the EMR for any updates post-surgery.

[0113] At the Surgical Data Server 180, an Episode of Care Database 185 is used to store the various data collected over a patient's episode of care. The Episode of Care Database 185 may be implemented using any technique known in the art. For example, in some embodiments, a SQL-based database may be used where all of the various data items are structured in a manner that allows them to be readily incorporated in two SQL's collection of rows and columns. However, in other embodiments a No-SQL database may be employed to allow for unstructured data, while providing the ability to rapidly process and respond to queries. As is understood in the art, the term "No-SQL" is used to define a class of data stores that are non-relational in their design. Various types of No-SQL databases may generally be grouped according to their underlying data model. These groupings may include databases that use column-based data models (e.g., Cassandra), document-based data models (e.g., MongoDB), key-value based data models (e.g., Redis), and/or graph-based data models (e.g., Allego). Any type of No-SQL database may be used to implement the various embodiments described herein and, in some embodiments, the different types of databases may support the Episode of Care Database 185.

[0114] Data can be transferred between the various data sources and the Surgical Data Server 180 using any data format and transfer technique known in the art. It should be noted that the architecture shown in FIG. 5C allows transmission from the data source to the Surgical Data Server 180, as well as retrieval of data from the Surgical Data Server 180 by the data sources. For example, as explained in detail below, in some embodiments, the Surgical Computer 150 may use data from past surgeries, machine learning models, etc. to help guide the surgical procedure.

[0115] In some embodiments, the Surgical Computer 150 or the Surgical Data Server 180 may execute a de-identification process to ensure that data stored in the Episode of Care

Database 185 meets Health Insurance Portability and Accountability Act (HIPAA) standards or other requirements mandated by law. HIPAA provides a list of certain identifiers that must be removed from data during de-identification. The aforementioned de-identification process can scan for these identifiers in data that is transferred to the Episode of Care Database 185 for storage. For example, in one embodiment, the Surgical Computer 150 executes the de-identification process just prior to initiating transfer of a particular data item or set of data items to the Surgical Data Server 180. In some embodiments, a unique identifier is assigned to data from a particular episode of care to allow for re-identification of the data if necessary.

[0116] Although FIGS. 5A – 5C discuss data collection in the context of a single episode of care, it should be understood that the general concept can be extended to data collection from multiple episodes of care. For example, surgical data may be collected over an entire episode of care each time a surgery is performed with the CASS 100 and stored at the Surgical Computer 150 or at the Surgical Data Server 180. As explained in further detail below, a robust database of episode of care data allows the generation of optimized values, measurements, distances, or other parameters and other recommendations related to the surgical procedure. In some embodiments, the various datasets are indexed in the database or other storage medium in a manner that allows for rapid retrieval of relevant information during the surgical procedure. For example, in one embodiment, a patient-centric set of indices may be used so that data pertaining to a particular patient or a set of patients similar to a particular patient can be readily extracted. This concept can be similarly applied to surgeons, implant characteristics, CASS component versions, etc.

[0117] Further details of the management of episode of care data is described in U.S. Patent Application No. 62/783,858 filed December 21, 2018 and entitled "Methods and Systems for Providing an Episode of Care," the entirety of which is incorporated herein by reference.

Open versus Closed Digital Ecosystems

[0118] In some embodiments, the CASS 100 is designed to operate as a self-contained or "closed" digital ecosystem. Each component of the CASS 100 is specifically designed to be used in the closed ecosystem, and data is generally not accessible to devices outside of the digital ecosystem. For example, in some embodiments, each component includes software or firmware that implements proprietary protocols for activities such as communication, storage, security, etc. The concept of a closed digital ecosystem may be desirable for a company that wants to control all components of the CASS 100 to ensure that certain compatibility, security, and reliability

standards are met. For example, the CASS 100 can be designed such that a new component cannot be used with the CASS unless it is certified by the company.

[0119] In other embodiments, the CASS 100 is designed to operate as an "open" digital ecosystem. In these embodiments, components may be produced by a variety of different companies according to standards for activities, such as communication, storage, and security. Thus, by using these standards, any company can freely build an independent, compliant component of the CASS platform. Data may be transferred between components using publicly available application programming interfaces (APIs) and open, shareable data formats.

[0120] To illustrate one type of recommendation that may be performed with the CASS 100, a technique for optimizing surgical parameters is disclosed below. The term "optimization" in this context means selection of parameters that are optimal based on certain specified criteria. In an extreme case, optimization can refer to selecting optimal parameter(s) based on data from the entire episode of care, including any pre-operative data, the state of CASS data at a given point in time, and post-operative goals. Moreover, optimization may be performed using historical data, such as data generated during past surgeries involving, for example, the same surgeon, past patients with physical characteristics similar to the current patient, or the like.

[0121] The optimized parameters may depend on the portion of the patient's anatomy to be operated on. For example, for knee surgeries, the surgical parameters may include positioning information for the femoral and tibial component including, without limitation, rotational alignment (e.g., varus/valgus rotation, external rotation, flexion rotation for the femoral component, posterior slope of the tibial component), resection depths (e.g., varus knee, valgus knee), and implant type, size and position. The positioning information may further include surgical parameters for the combined implant, such as overall limb alignment, combined tibiofemoral hyperextension, and combined tibiofemoral resection. Additional examples of parameters that could be optimized for a given TKA femoral implant by the CASS 100 include the following:

Parameter	**Reference**	**Exemplary Recommendation (s)**
Size	Posterior	The largest sized implant that does not overhang medial/lateral bone edges or overhang the

		anterior femur. A size that does not result in overstuffing the patella femoral joint
Implant Position – Medial Lateral	Medial/lateral cortical bone edges	Center the implant evenly between the medial/lateral cortical bone edges
Resection Depth – Varus Knee	Distal and posterior lateral	6 mm of bone
Resection Depth – Valgus Knee	Distal and posterior medial	7 mm of bone
Rotation - Varus/Valgus	Mechanical Axis	1° varus
Rotation - External	Transepicondylar Axis	1° external from the transepicondylar axis
Rotation – Flexion	Mechanical Axis	3° flexed

[0122] Additional examples of parameters that could be optimized for a given TKA tibial implant by the CASS 100 include the following:

Parameter	**Reference**	**Exemplary Recommendation (s)**
Size	Posterior	The largest sized implant that does not overhang the medial, lateral, anterior, and posterior tibial edges
Implant Position	Medial/lateral and anterior/posterior cortical bone edges	Center the implant evenly between the medial/lateral and anterior/posterior cortical bone edges
Resection Depth – Varus Knee	Lateral/Medial	4 mm of bone
Resection Depth – Valgus Knee	Lateral/Medial	5 mm of bone
Rotation - Varus/Valgus	Mechanical Axis	1° valgus
Rotation - External	Tibial Anterior Posterior Axis	1° external from the tibial anterior paxis
Posterior Slope	Mechanical Axis	3° posterior slope

[0123] For hip surgeries, the surgical parameters may comprise femoral neck resection location and angle, cup inclination angle, cup anteversion angle, cup depth, femoral stem design, femoral stem size, fit of the femoral stem within the canal, femoral offset, leg length, and femoral version of the implant.

[0124] Shoulder parameters may include, without limitation, humeral resection depth/angle, humeral stem version, humeral offset, glenoid version and inclination, as well as reverse shoulder parameters such as humeral resection depth/angle, humeral stem version, Glenoid tilt/version, glenosphere orientation, glenosphere offset and offset direction.

[0125] Various conventional techniques exist for optimizing surgical parameters. However, these techniques are typically computationally intensive and, thus, parameters often need to be determined pre-operatively. As a result, the surgeon is limited in his or her ability to make modifications to optimized parameters based on issues that may arise during surgery. Moreover, conventional optimization techniques typically operate in a "black box" manner with little or no explanation regarding recommended parameter values. Thus, if the surgeon decides to deviate from a recommended parameter value, the surgeon typically does so without a full understanding of the effect of that deviation on the rest of the surgical workflow, or the impact of the deviation on the patient's post-surgery quality of life.

Operative Patient Care System

[0126] The general concepts of optimization may be extended to the entire episode of care using an Operative Patient Care System 620 that uses the surgical data, and other data from the Patient 605 and Healthcare Professionals 630 to optimize outcomes and patient satisfaction as depicted in FIG. 6.

[0127] Conventionally, pre-operative diagnosis, pre-operative surgical planning, intraoperative execution of a prescribed plan, and post-operative management of total joint arthroplasty are based on individual experience, published literature, and training knowledge bases of surgeons (ultimately, tribal knowledge of individual surgeons and their 'network' of peers and journal publications) and their native ability to make accurate intraoperative tactile discernment of "balance" and accurate manual execution of planar resections using guides and visual cues. This existing knowledge base and execution is limited with respect to the outcomes

optimization offered to patients needing care. For example, limits exist with respect to accurately diagnosing a patient to the proper, least-invasive prescribed care; aligning dynamic patient, healthcare economic, and surgeon preferences with patient-desired outcomes; executing a surgical plan resulting in proper bone alignment and balance, etc.; and receiving data from disconnected sources having different biases that are difficult to reconcile into a holistic patient framework. Accordingly, a data-driven tool that more accurately models anatomical response and guides the surgical plan can improve the existing approach.

[0128] The Operative Patient Care System 620 is designed to utilize patient specific data, surgeon data, healthcare facility data, and historical outcome data to develop an algorithm that suggests or recommends an optimal overall treatment plan for the patient's entire episode of care (preoperative, operative, and postoperative) based on a desired clinical outcome. For example, in one embodiment, the Operative Patient Care System 620 tracks adherence to the suggested or recommended plan, and adapts the plan based on patient/care provider performance. Once the surgical treatment plan is complete, collected data is logged by the Operative Patient Care System 620 in a historical database. This database is accessible for future patients and the development of future treatment plans. In addition to utilizing statistical and mathematical models, simulation tools (e.g., LIFEMOD®) can be used to simulate outcomes, alignment, kinematics, etc. based on a preliminary or proposed surgical plan, and reconfigure the preliminary or proposed plan to achieve desired or optimal results according to a patient's profile or a surgeon's preferences. The Operative Patient Care System 620 ensures that each patient is receiving personalized surgical and rehabilitative care, thereby improving the chance of successful clinical outcomes and lessening the economic burden on the facility associated with near-term revision.

[0129] In some embodiments, the Operative Patient Care System 620 employs a data collecting and management method to provide a detailed surgical case plan with distinct steps that are monitored and/or executed using a CASS 100. The performance of the user(s) is calculated at the completion of each step and can be used to suggest changes to the subsequent steps of the case plan. Case plan generation relies on a series of input data that is stored on a local or cloud-storage database. Input data can be related to both the current patient undergoing treatment and historical data from patients who have received similar treatment(s).

[0130] A Patient 605 provides inputs such as Current Patient Data 610 and Historical Patient Data 615 to the Operative Patient Care System 620. Various methods generally known in the art may be used to gather such inputs from the Patient 605. For example, in some embodiments, the Patient 605 fills out a paper or digital survey that is parsed by the Operative Patient Care System 620 to extract patient data. In other embodiments, the Operative Patient Care System 620 may extract patient data from existing information sources, such as electronic medical records (EMRs), health history files, and payer/provider historical files. In still other embodiments, the Operative Patient Care System 620 may provide an application program interface (API) that allows the external data source to push data to the Operative Patient Care System. For example, the Patient 605 may have a mobile phone, wearable device, or other mobile device that collects data (e.g., heart rate, pain or discomfort levels, exercise or activity levels, or patient-submitted responses to the patient's adherence with any number of pre-operative plan criteria or conditions) and provides that data to the Operative Patient Care System 620. Similarly, the Patient 605 may have a digital application on his or her mobile or wearable device that enables data to be collected and transmitted to the Operative Patient Care System 620.

[0131] Current Patient Data 610 can include, but is not limited to, activity level, preexisting conditions, comorbidities, prehab performance, health and fitness level, pre-operative expectation level (relating to hospital, surgery, and recovery), a Metropolitan Statistical Area (MSA) driven score, genetic background, prior injuries (sports, trauma, etc.), previous joint arthroplasty, previous trauma procedures, previous sports medicine procedures, treatment of the contralateral joint or limb, gait or biomechanical information (back and ankle issues), levels of pain or discomfort, care infrastructure information (payer coverage type, home health care infrastructure level, etc.), and an indication of the expected ideal outcome of the procedure.

[0132] Historical Patient Data 615 can include, but is not limited to, activity level, preexisting conditions, comorbidities, prehab performance, health and fitness level, pre-operative expectation level (relating to hospital, surgery, and recovery), a MSA driven score, genetic background, prior injuries (sports, trauma, etc.), previous joint arthroplasty, previous trauma procedures, previous sports medicine procedures, treatment of the contralateral joint or limb, gait or biomechanical information (back and ankle issues), levels or pain or discomfort, care infrastructure information (payer coverage type, home health care infrastructure level, etc.), expected ideal outcome of the procedure, actual outcome of the procedure (patient reported

outcomes [PROs], survivorship of implants, pain levels, activity levels, etc.), sizes of implants used, position/orientation/alignment of implants used, soft-tissue balance achieved, etc.

[0133] Healthcare Professional(s) 630 conducting the procedure or treatment may provide various types of data 625 to the Operative Patient Care System 620. This Healthcare Professional Data 625 may include, for example, a description of a known or preferred surgical technique (e.g., Cruciate Retaining (CR) vs Posterior Stabilized (PS), up- vs down-sizing, tourniquet vs tourniquet-less, femoral stem style, preferred approach for THA, etc.), the level of training of the Healthcare Professional(s) 630 (e.g., years in practice, fellowship trained, where they trained, whose techniques they emulate), previous success level including historical data (outcomes, patient satisfaction), and the expected ideal outcome with respect to range of motion, days of recovery, and survivorship of the device. The Healthcare Professional Data 625 can be captured, for example, with paper or digital surveys provided to the Healthcare Professional 630, via inputs to a mobile application by the Healthcare Professional, or by extracting relevant data from EMRs. In addition, the CASS 100 may provide data such as profile data (e.g., a Patient Specific Knee Instrument Profile) or historical logs describing use of the CASS during surgery.

[0134] Information pertaining to the facility where the procedure or treatment will be conducted may be included in the input data. This data can include, without limitation, the following: Ambulatory Surgery Center (ASC) vs hospital, facility trauma level, Comprehensive Care for Joint Replacement Program (CJR) or bundle candidacy, a MSA driven score, community vs metro, academic vs non-academic, postoperative network access (Skilled Nursing Facility [SNF] only, Home Health, etc.), availability of medical professionals, implant availability, and availability of surgical equipment.

[0135] These facility inputs can be captured by, for example and without limitation, Surveys (Paper/Digital), Surgery Scheduling Tools (e.g., apps, Websites, Electronic Medical Records [EMRs], etc.), Databases of Hospital Information (on the Internet), etc. Input data relating to the associated healthcare economy including, but not limited to, the socioeconomic profile of the patient, the expected level of reimbursement the patient will receive, and if the treatment is patient specific may also be captured.

[0136] These healthcare economic inputs can be captured by, for example and without limitation, Surveys (Paper/Digital), Direct Payer Information, Databases of Socioeconomic status (on the Internet with zip code), etc. Finally, data derived from simulation of the procedure is

captured. Simulation inputs include implant size, position, and orientation. Simulation can be conducted with custom or commercially available anatomical modeling software programs (e.g., LIFEMOD®, AnyBody, or OpenSIM). It is noted that the data inputs described above may not be available for every patient, and the treatment plan will be generated using the data that is available.

[0137] Prior to surgery, the Patient Data 610, 615 and Healthcare Professional Data 625 may be captured and stored in a cloud-based or online database (e.g., the Surgical Data Server 180 shown in FIG. 5C). Information relevant to the procedure is supplied to a computing system via wireless data transfer or manually with the use of portable media storage. The computing system is configured to generate a case plan for use with a CASS 100. Case plan generation will be described hereinafter. It is noted that the system has access to historical data from previous patients undergoing treatment, including implant size, placement, and orientation as generated by a computer-assisted, patient-specific knee instrument (PSKI) selection system, or automatically by the CASS 100 itself. To achieve this, case log data is uploaded to the historical database by a surgical sales rep or case engineer using an online portal. In some embodiments, data transfer to the online database is wireless and automated.

[0138] Historical data sets from the online database are used as inputs to a machine learning model such as, for example, a recurrent neural network (RNN) or other form of artificial neural network. As is generally understood in the art, an artificial neural network functions similar to a biologic neural network and is comprised of a series of nodes and connections. The machine learning model is trained to predict one or more values based on the input data. For the sections that follow, it is assumed that the machine learning model is trained to generate predictor equations. These predictor equations may be optimized to determine the optimal size, position, and orientation of the implants to achieve the best outcome or satisfaction level.

[0139] Once the procedure is complete, all patient data and available outcome data, including the implant size, position and orientation determined by the CASS 100, are collected and stored in the historical database. Any subsequent calculation of the target equation via the RNN will include the data from the previous patient in this manner, allowing for continuous improvement of the system.

[0140] In addition to, or as an alternative to determining implant positioning, in some embodiments, the predictor equation and associated optimization can be used to generate the

resection planes for use with a PSKI system. When used with a PSKI system, the predictor equation computation and optimization are completed prior to surgery. Patient anatomy is estimated using medical image data (x-ray, CT, MRI). Global optimization of the predictor equation can provide an ideal size and position of the implant components. Boolean intersection of the implant components and patient anatomy is defined as the resection volume. PSKI can be produced to remove the optimized resection envelope. In this embodiment, the surgeon cannot alter the surgical plan intraoperatively.

[0141] The surgeon may choose to alter the surgical case plan at any time prior to or during the procedure. If the surgeon elects to deviate from the surgical case plan, the altered size, position, and/or orientation of the component(s) is locked, and the global optimization is refreshed based on the new size, position, and/or orientation of the component(s) (using the techniques previously described) to find the new ideal position of the other component(s) and the corresponding resections needed to be performed to achieve the newly optimized size, position and/or orientation of the component(s). For example, if the surgeon determines that the size, position and/or orientation of the femoral implant in a TKA needs to be updated or modified intraoperatively, the femoral implant position is locked relative to the anatomy, and the new optimal position of the tibia will be calculated (via global optimization) considering the surgeon's changes to the femoral implant size, position and/or orientation. Furthermore, if the surgical system used to implement the case plan is robotically assisted (e.g., as with NAVIO® or the MAKO Rio), bone removal and bone morphology during the surgery can be monitored in real time. If the resections made during the procedure deviate from the surgical plan, the subsequent placement of additional components may be optimized by the processor taking into account the actual resections that have already been made.

[0142] FIG. 7A illustrates how the Operative Patient Care System 620 may be adapted for performing case plan matching services. In this example, data is captured relating to the current patient 610 and is compared to all or portions of a historical database of patient data and associated outcomes 615. For example, the surgeon may elect to compare the plan for the current patient against a subset of the historical database. Data in the historical database can be filtered to include, for example, only data sets with favorable outcomes, data sets corresponding to historical surgeries of patients with profiles that are the same or similar to the current patient profile, data sets corresponding to a particular surgeon, data sets corresponding to a particular

element of the surgical plan (e.g., only surgeries where a particular ligament is retained), or any other criteria selected by the surgeon or medical professional. If, for example, the current patient data matches or is correlated with that of a previous patient who experienced a good outcome, the case plan from the previous patient can be accessed and adapted or adopted for use with the current patient. The predictor equation may be used in conjunction with an intraoperative algorithm that identifies or determines the actions associated with the case plan. Based on the relevant and/or preselected information from the historical database, the intraoperative algorithm determines a series of recommended actions for the surgeon to perform. Each execution of the algorithm produces the next action in the case plan. If the surgeon performs the action, the results are evaluated. The results of the surgeon's performing the action are used to refine and update inputs to the intraoperative algorithm for generating the next step in the case plan. Once the case plan has been fully executed all data associated with the case plan, including any deviations performed from the recommended actions by the surgeon, are stored in the database of historical data. In some embodiments, the system utilizes preoperative, intraoperative, or postoperative modules in a piecewise fashion, as opposed to the entire continuum of care. In other words, caregivers can prescribe any permutation or combination of treatment modules including the use of a single module. These concepts are illustrated in FIG. 7B and can be applied to any type of surgery utilizing the CASS 100.

Surgery Process Display

[0143] As noted above with respect to FIGS. 1 and 5A-5C, the various components of the CASS 100 generate detailed data records during surgery. The CASS 100 can track and record various actions and activities of the surgeon during each step of the surgery and compare actual activity to the pre-operative or intraoperative surgical plan. In some embodiments, a software tool may be employed to process this data into a format where the surgery can be effectively "played-back." For example, in one embodiment, one or more GUIs may be used that depict all of the information presented on the Display 125 during surgery. This can be supplemented with graphs and images that depict the data collected by different tools. For example, a GUI that provides a visual depiction of the knee during tissue resection may provide the measured torque and displacement of the resection equipment adjacent to the visual depiction to better provide an understanding of any deviations that occurred from the planned resection area. The ability to review a playback of the surgical plan or toggle between different phases of the actual surgery

vs. the surgical plan could provide benefits to the surgeon and/or surgical staff, allowing such persons to identify any deficiencies or challenging phases of a surgery so that they can be modified in future surgeries. Similarly, in academic settings, the aforementioned GUIs can be used as a teaching tool for training future surgeons and/or surgical staff. Additionally, because the data set effectively records many elements of the surgeon's activity, it may also be used for other reasons (e.g., legal or compliance reasons) as evidence of correct or incorrect performance of a particular surgical procedure.

[0144] Over time, as more and more surgical data is collected, a rich library of data may be acquired that describes surgical procedures performed for various types of anatomy (knee, shoulder, hip, etc.) by different surgeons for different patients. Moreover, information such as implant type and dimension, patient demographics, etc. can further be used to enhance the overall dataset. Once the dataset has been established, it may be used to train a machine learning model (e.g., RNN) to make predictions of how surgery will proceed based on the current state of the CASS 100.

[0145] Training of the machine learning model can be performed as follows. The overall state of the CASS 100 can be sampled over a plurality of time periods for the duration of the surgery. The machine learning model can then be trained to translate a current state at a first time period to a future state at a different time period. By analyzing the entire state of the CASS 100 rather than the individual data items, any causal effects of interactions between different components of the CASS 100 can be captured. In some embodiments, a plurality of machine learning models may be used rather than a single model. In some embodiments, the machine learning model may be trained not only with the state of the CASS 100, but also with patient data (e.g., captured from an EMR) and an identification of members of the surgical staff. This allows the model to make predictions with even greater specificity. Moreover, it allows surgeons to selectively make predictions based only on their own surgical experiences if desired.

[0146] In some embodiments, predictions or recommendations made by the aforementioned machine learning models can be directly integrated into the surgical workflow. For example, in some embodiments, the Surgical Computer 150 may execute the machine learning model in the background making predictions or recommendations for upcoming actions or surgical conditions. A plurality of states can thus be predicted or recommended for each period. For example, the Surgical Computer 150 may predict or recommend the state for the next 5 minutes

in 30 second increments. Using this information, the surgeon can utilize a "process display" view of the surgery that allows visualization of the future state. For example, FIG. 7C depicts a series of images that may be displayed to the surgeon depicting the implant placement interface. The surgeon can cycle through these images, for example, by entering a particular time into the display 125 of the CASS 100 or instructing the system to advance or rewind the display in a specific time increment using a tactile, oral, or other instruction. In one embodiment, the process display can be presented in the upper portion of the surgeon's field of view in the AR HMD. In some embodiments, the process display can be updated in real-time. For example, as the surgeon moves resection tools around the planned resection area, the process display can be updated so that the surgeon can see how his or her actions are affecting the other factors of the surgery.

[0147] In some embodiments, rather than simply using the current state of the CASS 100 as an input to the machine learning model, the inputs to the model may include a planned future state. For example, the surgeon may indicate that he or she is planning to make a particular bone resection of the knee joint. This indication may be entered manually into the Surgical Computer 150 or the surgeon may verbally provide the indication. The Surgical Computer 150 can then produce a film strip showing the predicted effect of the cut on the surgery. Such a film strip can depict over specific time increments how the surgery will be affected, including, for example, changes in the patient's anatomy, changes to implant position and orientation, and changes regarding surgical intervention and instrumentation, if the contemplated course of action were to be performed. A surgeon or medical professional can invoke or request this type of film strip at any point in the surgery to preview how a contemplated course of action would affect the surgical plan if the contemplated action were to be carried out.

[0148] It should be further noted that, with a sufficiently trained machine learning model and robotic CASS, various elements of the surgery can be automated such that the surgeon only needs to be minimally involved, for example, by only providing approval for various steps of the surgery. For example, robotic control using arms or other means can be gradually integrated into the surgical workflow over time with the surgeon slowly becoming less and less involved with manual interaction versus robot operation. The machine learning model in this case can learn what robotic commands are required to achieve certain states of the CASS-implemented plan. Eventually, the machine learning model may be used to produce a film strip or similar view or display that predicts and can preview the entire surgery from an initial state. For example, an

initial state may be defined that includes the patient information, the surgical plan, implant characteristics, and surgeon preferences. Based on this information, the surgeon could preview an entire surgery to confirm that the CASS-recommended plan meets the surgeon's expectations and/or requirements. Moreover, because the output of the machine learning model is the state of the CASS 100 itself, commands can be derived to control the components of the CASS to achieve each predicted state. In the extreme case, the entire surgery could thus be automated based on just the initial state information.

Using the Point Probe to Acquire High-Resolution of Key Areas during Hip Surgeries

[0149] Use of the point probe is described in U.S. Patent Application No. 14/955,742 entitled "Systems and Methods for Planning and Performing Image Free Implant Revision Surgery," the entirety of which is incorporated herein by reference. Briefly, an optically tracked point probe may be used to map the actual surface of the target bone that needs a new implant. Mapping is performed after removal of the defective or worn-out implant, as well as after removal of any diseased or otherwise unwanted bone. A plurality of points is collected on the bone surfaces by brushing or scraping the entirety of the remaining bone with the tip of the point probe. This is referred to as tracing or "painting" the bone. The collected points are used to create a three-dimensional model or surface map of the bone surfaces in the computerized planning system. The created 3D model of the remaining bone is then used as the basis for planning the procedure and necessary implant sizes. An alternative technique that uses X-rays to determine a 3D model is described in U.S. Patent Application No. 16/387,151, filed April 17, 2019 and entitled "Three-Dimensional Selective Bone Matching" and U.S. Patent Application No. 16/789,930, filed February 13, 2020 and entitled "Three-Dimensional Selective Bone Matching," the entirety of each of which is incorporated herein by reference.

[0150] For hip applications, the point probe painting can be used to acquire high resolution data in key areas such as the acetabular rim and acetabular fossa. This can allow a surgeon to obtain a detailed view before beginning to ream. For example, in one embodiment, the point probe may be used to identify the floor (fossa) of the acetabulum. As is well understood in the art, in hip surgeries, it is important to ensure that the floor of the acetabulum is not compromised during reaming so as to avoid destruction of the medial wall. If the medial wall were inadvertently destroyed, the surgery would require the additional step of bone grafting. With this in mind, the information from the point probe can be used to provide operating guidelines to the

acetabular reamer during surgical procedures. For example, the acetabular reamer may be configured to provide haptic feedback to the surgeon when he or she reaches the floor or otherwise deviates from the surgical plan. Alternatively, the CASS 100 may automatically stop the reamer when the floor is reached or when the reamer is within a threshold distance.

[0151] As an additional safeguard, the thickness of the area between the acetabulum and the medial wall could be estimated. For example, once the acetabular rim and acetabular fossa has been painted and registered to the pre-operative 3D model, the thickness can readily be estimated by comparing the location of the surface of the acetabulum to the location of the medial wall. Using this knowledge, the CASS 100 may provide alerts or other responses in the event that any surgical activity is predicted to protrude through the acetabular wall while reaming.

[0152] The point probe may also be used to collect high resolution data of common reference points used in orienting the 3D model to the patient. For example, for pelvic plane landmarks like the ASIS and the pubic symphysis, the surgeon may use the point probe to paint the bone to represent a true pelvic plane. Given a more complete view of these landmarks, the registration software has more information to orient the 3D model.

[0153] The point probe may also be used to collect high-resolution data describing the proximal femoral reference point that could be used to increase the accuracy of implant placement. For example, the relationship between the tip of the Greater Trochanter (GT) and the center of the femoral head is commonly used as reference point to align the femoral component during hip arthroplasty. The alignment is highly dependent on proper location of the GT; thus, in some embodiments, the point probe is used to paint the GT to provide a high-resolution view of the area. Similarly, in some embodiments, it may be useful to have a high-resolution view of the Lesser Trochanter (LT). For example, during hip arthroplasty, the Dorr Classification helps to select a stem that will maximize the ability of achieving a press-fit during surgery to prevent micromotion of femoral components post-surgery and ensure optimal bony ingrowth. As is generated understood in the art, the Dorr Classification measures the ratio between the canal width at the LT and the canal width 10 cm below the LT. The accuracy of the classification is highly dependent on the correct location of the relevant anatomy. Thus, it may be advantageous to paint the LT to provide a high-resolution view of the area.

[0154] In some embodiments, the point probe is used to paint the femoral neck to provide high-resolution data that allows the surgeon to better understand where to make the neck cut.

The navigation system can then guide the surgeon as they perform the neck cut. For example, as understood in the art, the femoral neck angle is measured by placing one line down the center of the femoral shaft and a second line down the center of the femoral neck. Thus, a high-resolution view of the femoral neck (and possibly the femoral shaft as well) would provide a more accurate calculation of the femoral neck angle.

[0155] High-resolution femoral head neck data also could be used for a navigated resurfacing procedure where the software/hardware aids the surgeon in preparing the proximal femur and placing the femoral component. As is generally understood in the art, during hip resurfacing, the femoral head and neck are not removed; rather, the head is trimmed and capped with a smooth metal covering. In this case, it would be advantageous for the surgeon to paint the femoral head and cap so that an accurate assessment of their respective geometries can be understood and used to guide trimming and placement of the femoral component.

Registration of Pre-operative Data to Patient Anatomy using the Point Probe

[0156] As noted above, in some embodiments, a 3D model is developed during the pre-operative stage based on 2D or 3D images of the anatomical area of interest. In such embodiments, registration between the 3D model and the surgical site is performed prior to the surgical procedure. The registered 3D model may be used to track and measure the patient's anatomy and surgical tools intraoperatively.

[0157] During the surgical procedure, landmarks are acquired to facilitate registration of this pre-operative 3D model to the patient's anatomy. For knee procedures, these points could comprise the femoral head center, distal femoral axis point, medial and lateral epicondyles, medial and lateral malleolus, proximal tibial mechanical axis point, and tibial A/P direction. For hip procedures these points could comprise the anterior superior iliac spine (ASIS), the pubic symphysis, points along the acetabular rim and within the hemisphere, the greater trochanter (GT), and the lesser trochanter (LT).

[0158] In a revision surgery, the surgeon may paint certain areas that contain anatomical defects to allow for better visualization and navigation of implant insertion. These defects can be identified based on analysis of the pre-operative images. For example, in one embodiment, each pre-operative image is compared to a library of images showing "healthy" anatomy (i.e., without defects). Any significant deviations between the patient's images and the healthy images can be flagged as a potential defect. Then, during surgery, the surgeon can be warned of the possible

defect via a visual alert on the display 125 of the CASS 100. The surgeon can then paint the area to provide further detail regarding the potential defect to the Surgical Computer 150.

[0159] In some embodiments, the surgeon may use a non-contact method for registration of bony anatomy intra-incision. For example, in one embodiment, laser scanning is employed for registration. A laser stripe is projected over the anatomical area of interest and the height variations of the area are detected as changes in the line. Other non-contact optical methods, such as white light interferometry or ultrasound, may alternatively be used for surface height measurement or to register the anatomy. For example, ultrasound technology may be beneficial where there is soft tissue between the registration point and the bone being registered (e.g., ASIS, pubic symphysis in hip surgeries), thereby providing for a more accurate definition of anatomic planes.

Arthroscopic Video Analysis

[0160] Referring to FIG. 8, a system 80 for arthroscopic video analysis can be used to generate a video of an arthroscopic procedure having one or more analytics, generated using machine learning models, associated therewith. The one or more analytics can be displayed as overlays on the video or the overlays could be used to generate anatomical region-specific bitmasks to apply processing specific to that anatomical region. In one example, the analytical information can be displayed on the video in real-time to provide real-time, contextual feedback during the surgical procedure. The system 80 includes an arthroscopic camera 810 that provides raw unprocessed arthroscopic video data 830. The arthroscopic video data 830 is received by an arthroscopic video analysis system 820 and/or an arthroscopic video analysis apparatus 825, which can be included as part of the arthroscopic video analysis system 820 in some examples. In some examples, the arthroscopic camera 810 and the arthroscopic video analysis system 820 can be part of the same device that generates video feeds of an arthroscopic procedure. Using the system 80, an operator can acquire the raw unprocessed arthroscopic video data 830 for an anatomical region of interest, such as a patient's joint, although the system 80 can be used for other anatomical regions of interest. The joint can be, for example, a knee, hip, shoulder, or any other joint or structure. In some examples, the arthroscopic video analysis system 820 and/or the arthroscopic video analysis apparatus 825 are communicably coupled to one or more sync devices 870 such as a surgical monitor, printers, video capture systems, etc. In one example, the

arthroscopic video analysis system 820 and/or the arthroscopic video analysis apparatus 25 are communicably coupled to the surgical computer 150 of the CASS system shown in FIG. 1, such as via the network 175, although the arthroscopic video analysis system 820 and/or the arthroscopic video analysis apparatus 825 may be utilized in or with other CASS systems. The arthroscopic video analysis system 820 and/or the arthroscopic video analysis apparatus 825 can also be coupled to one or more cloud and/or local network server devices 850 via one or more communication network(s). The cloud and/or local network server devices can provide repositories containing pre-operative data 860 that enable machine learning models stored in the arthroscopic video analysis apparatus 825, for example, to customize the analytical output, as described in further detail below. The pre-operative data 860 can include patient metadata (PHI, procedure type, etc.), video data (MRI/CT data used for video registration for a video only based navigation system), or alternate learning models, by way of example only.

[0161] The raw arthroscopic video data 830 is processed as a two-dimensional video feed of the anatomical region in the field of view of the arthroscopic camera 810, as described and illustrated in more detail herein with reference to FIGS. 8-13 to generate processed arthroscopic video data 840. The video feed can be processed using machine learning models, for example, to generate analytical information regarding the surgical procedure that can be overlaid onto the generated video feed. For example, the analytical information can include identification of anatomical structures in the field of view, such as a joint, identification of pathologies or defects, or making one or more measurements in the field of view of the arthroscopic camera 810. As an example, the analytical information can be merged with the video feed as one or more overlays in the processed video surgical data 840.

[0162] The processed video surgical data 840 can be stored and/or transferred to other devices, such as sync devices 870 or the surgical computer 150. In one example, the processed video surgical data 840 can be used to display relevant information in real-time to the surgeon. The analytical information provides contextual information regarding the procedure. This analytical information can be used in real-time embodiments to assist the surgical procedure intraoperatively. In another example, the analytical information can be composed of bitmasks of specific anatomical regions generated by the arthroscopic video analysis apparatus 825 to be used by the arthroscopic video analysis system 820 to apply specific enhancements to particular anatomical regions (e.g., vascularization enhance of meniscal vasculature, or cartilage damage of

condular cartilage) in the processed arthroscopic video data 840. Alternatively, the video feed with the analytical overlays can be utilized as a training tool in a playback of the processed arthroscopic video data 840 as a video feed. As another example, the processed arthroscopic video data 840 can include analytical information regarding the surgery that can be used to provide an identification of current procedural terminology (CPT) codes to assist in a billing workflow, although any other uses of the video feeds including the generated and overlaid analytical information are contemplated.

[0163] The arthroscopic camera 810 in this example includes a camera configured to provide a video feed of an arthroscopic procedure. In one example, the arthroscopic camera 810 can provide a high-resolution video feed, such as 4k with a rate of 60 frames/second, although other cameras can be employed. In one example, the arthroscopic camera is part of an endoscopic device. The endoscopic device can be part of a system that also includes an arthroscopic video analysis system 820. One example of a system that includes an arthroscopic camera 810 associated with an endoscopic device is the LENS™ system from SMITH AND NEPHEW, INC. The arthroscopic camera 810 is configured to provide a video feed of anatomical regions subject to an arthroscopic surgery, such as a knee joint. In one implementation, the arthroscopic camera 10 has spectral capabilities.

[0164] To acquire the arthroscopic video data 830 using the system 80, a human operator locates the arthroscopic camera 810 to provide the anatomical region of interest in the field of view of the arthroscopic camera 810, such as by placing an endoscopic device including the arthroscopic camera 810 in proximity to the joint. In another example, the arthroscopic camera 810 could be positioned using the computer-assisted surgical system disclosed herein. The arthroscopic video data 830 can include a video feed that extends for the entire duration of the arthroscopic surgical procedure. In this example, the arthroscopic video data 830 is a real-time stream as opposed to a static container, such as an mp4 file. The arthroscopic camera 810 can be relocated during the procedure, either by the human operator or by computer assistance, to obtain arthroscopic video data 830 for different fields of view.

[0165] During the arthroscopic surgical procedure, the arthroscopic video analysis system 820 and/or the arthroscopic video analysis apparatus 825 receives the raw unprocessed video data 830, generates the processed arthroscopic video data 840 including the overlays, and stores and/or transmits the processed arthroscopic video data 840. The arthroscopic video analysis

system 820 provides pre-processing of the arthroscopic raw unprocessed video data 830 prior to analysis by the arthroscopic video analysis apparatus 825, although pre-processing can also be performed by the arthroscopic video analysis apparatus 825 in another example. Using the raw unprocessed arthroscopic video data 830, the arthroscopic video analysis apparatus 825, in some implementations, provides a two-dimensional video overlay feed that the arthroscopic video analysis system 820 merges with a view of the anatomical region in the field of view of the arthroscopic camera 810 during the surgical procedure to create the processed arthroscopic video data 840. The arthroscopic video analysis system 820 or arthroscopic video analysis apparatus 825 stores the processed arthroscopic video data 840 for post-operative video processing, or transmits the processed arthroscopic video data 840 to other devices, such as the sync devices 870, as described in further detail below. In other examples, the arthroscopic video analysis system 820 or arthroscopic video analysis apparatus 825 provides a real-time analysis in video format. The arthroscopic video data 830 can be processed, as described below, to provide intraoperative analytics on the displayed video feed in real-time.

[0166] Referring now to FIG. 9, a detailed view of the arthroscopic video analysis system 820 is shown. In this example, the arthroscopic video analysis system 820 includes one or more processor(s) 921, a bus 922, an on-screen display module 923, a video processing module 924, the arthroscopic video analysis apparatus 825, a post-processing module 926, and a video stream compositing module 927, although the arthroscopic video analysis system 820 can include other types and/or numbers of elements or components in other combinations. By way of example, the arthroscopic video analysis system 820 can include other electronics for video processing, such as splitting or merging video data, downsampling or compressing video data, providing overlays, etc. One or more of these functions can be carried out by field programmable gate arrays (FPGAs) of the arthroscopic video analysis system 820, although other hardware logic or programmed instructions can be employed for these functions.

[0167] The processor(s) 921 of the arthroscopic video analysis system 820 may execute programmed instructions stored in a memory for any number of the functions described and illustrated herein. The processor(s) 921 of the arthroscopic video analysis system 820 may include one or more central processing units (CPUs) or general purpose processors with one or more processing cores, for example, although other types of processor(s) can also be used. By way of example, the processor(s) 921 of the arthroscopic video analysis system 820 controls

which sources are blended into processed arthroscopic video data 940, generates on-screen display overlays for the user interface that are not part of the machine learning overlays developed by the arthroscopic video analysis apparatus 825, and coordinates input preoperative data to enable the machine learning analysis performed in the arthroscopic video analysis apparatus 825, although the processor(s) 921 in the arthroscopic video analysis system 820 may provide other types and/or number of functions. Bus 922 operatively couples the processor(s) 921 to the various peripheral components of the arthroscopic video analysis system 820.

[0168] The on-screen display module 923 is configured to provide one or more overlays that are not generated by the arthroscopic video analysis apparatus 825, but may be included in the output to the user interface for the arthroscopic video analysis system 820. The on-screen display module 923 provides the additional overlays to the video compositing module 927 to be included in the output processed arthroscopic video data 940.

[0169] Video processing module 924 receives the raw unprocessed arthroscopic video data 930. The video processing module 924 is configured to correct and enhance the raw resolution camera video data into a first video data stream 931 that can be provided to the video compositing module 927 to be presented intraoperatively on a display interface. The first video data stream 931 is a high resolution, low latency video stream that provides the anatomical field of view with no overlays or other on-screen displays. Video processing module 924 also provides a second video data stream 932 to the arthroscopic video analysis apparatus 825 for machine learning analysis as described below. In some examples, the second video data stream 932 is downsampled to enable low latency processing through the arthroscopic video analysis apparatus 825.

[0170] Referring now more specifically to FIGS. 9 and 10, the arthroscopic video analysis apparatus 825 may perform any number of functions, including processing the second video steam 932 to generate an analytical analysis of the video data as described below, although the arthroscopic video analysis apparatus 825 may perform other functions. The arthroscopic video analysis apparatus 825 outputs overlay information 933 regarding the anatomical regions in the second video stream 932. The overlay information 933 can be associated with analytical information, determined using machine learning models, that highlights or emphasizes anatomical structures of interest, pathologies or defects, or particular relevant measurements for the surgery related to the anatomical structures in the arthroscopic field of view. The overlay

information 933 may or may not include video data content. For example, in some embodiments, the overlay information may be within the surgical field of view or outside the surgical field of view as content in the surrounding screen space (e.g. the black screen space surrounding the arthroscopic surgical camera view). In additional embodiments, the overlay information may reflect one or more pieces of bone model information or surgical plan information. In a further embodiment, the overlay information may reflect current tool position relative to registered or labeled anatomy in a computer model. In a further example embodiment, the overlay information may reflect, mimic, or reference MRI, CT or any other known image modality. Moreover, the information may be displayed as 'registered overlay' on the surgical field of view, as a generic unscaled overlay in the surrounding screen space outside the surgical field of view, or a combination of the two.

[0171] The overlay information 933 is video formatted data in the form of analytical overlays correlated by position to anatomical areas in the first video stream 931. Alternatively, the overlay information 933 can be binary bitmasks of selected anatomical regions that correspond to positions in the first video stream 931.

[0172] The arthroscopic video analysis apparatus 825 in this example includes processor(s) 1054, a memory 1056, and a communication interface 1058, which are coupled together by a bus 1064, although the arthroscopic video analysis apparatus 825 can include other types or numbers of elements in other configurations in other examples.

[0173] The processor(s) 1054 of the arthroscopic video analysis apparatus 825 may execute programmed instructions stored in the memory 1056 of the arthroscopic video analysis apparatus 825 for any number of the functions described and illustrated herein. The processor(s) 1054 of the arthroscopic video analysis apparatus 825 may include one or more central processing units (CPUs) or general purpose processors with one or more processing cores, for example, although other types of processor(s) can also be used.

[0174] The memory 1056 of the arthroscopic video analysis apparatus 825 stores these programmed instructions for one or more aspects of the present technology as described and illustrated herein, although some or all of the programmed instructions could be stored elsewhere. A variety of different types of memory storage devices, such as random access memory (RAM), read only memory (ROM), hard disk, solid state drives (SSDs), flash memory, and/or any other computer readable medium which is read from and written to by a magnetic,

optical, or other reading and writing system that is coupled to the processor(s) 1054, can be used for the memory 1056.

[0175] Accordingly, the memory 1056 of the arthroscopic video analysis apparatus 825 can store one or more modules, such as a machine learning module, that can include computer executable instructions that, when executed by the arthroscopic video analysis apparatus 825, cause the arthroscopic video analysis apparatus 825 to perform actions, such as to execute one or more machine learning models on the second video stream 1032 to develop overlay information 1033, for example. The modules can be implemented as components of other modules. Further, the modules can be implemented as applications, operating system extensions, plugins, or the like.

[0176] In this particular example, the memory 1056 of the arthroscopic video analysis apparatus 825 includes a video processing module 1066. The video processing module 1066 in this example is configured to receive the second video stream 932, analyze the second video data stream 932, and apply machine learning models. In one example, the second video data stream 932 is downsampled video and video processing module 1066 is applied to the second video data stream 932 to allow for correlation to the real-time high resolution first video data steam 931. The video processing module 1066 can apply filtering and other video pre-processing techniques for analysis of the second video data stream 932. The operation of the video processing module 1066 in some examples is described and illustrated in more detail later with reference to FIGS.11-13.

[0177] Referring back to FIG. 8, the communication interface 1058 of the arthroscopic video analysis apparatus 825 is configured to operatively couple and enable communication between the arthroscopic video analysis apparatus 825 and the arthroscopic video analysis system 820 in some examples. In an example where the arthroscopic video analysis apparatus 825 is separate from the arthroscopic video analysis system 820, the arthroscopic video analysis apparatus 825 can be coupled to the arthroscopic video analysis system 820 by a direct, wired connection or communication network(s), for example, to feedback the analytical output of the arthroscopic video analysis apparatus 825 to the arthroscopic video analysis system 820, although other types of connections or configurations can also be used.

[0178] By way of example only, the connection(s) and/or communication network(s) can include local area network(s) (LAN(s)) that use TCP/IP over Ethernet and industry-standard

protocols, although other types or numbers of protocols or communication networks can be used. The communication network(s) in this example can employ any suitable interface mechanisms and network communication technologies including, for example, Ethernet-based Packet Data Networks (PDNs), and the like.

[0179] Referring again to FIG. 9, post-processing module 926 receives the overlay information from the arthroscopic video analysis apparatus 825. The post-processing module 926 outputs a third video data stream 934 that, in one example, is just a pass-through of the overlay information 933 from the arthroscopic video analysis apparatus 825. In the example where the overlay information 933 comprises binary bitmasks, the post-processing module 926 may generate the third video stream 934 as a high resolution endoscopic video stream where specific anatomical regions have been post-processed via the mask overlays in the overlay information 933.

[0180] Video stream compositing module 927 receives overlays from the on screen display module, the high resolution, low latency first video data stream 931 and the third video data stream including the overlay information 933 generated by the arthroscopic video analysis apparatus 825. The video stream compositing module 927 combines the various inputs based on instructions received from the processor(s) 921 of the arthroscopic video analysis system 820 to generate the processed arthroscopic video data 940, optionally including the analytical overlay information generated by the arthroscopic video analysis apparatus 825 using the machine learning models. By way of example, processed arthroscopic video data 940 provides a high resolution, low latency video stream including the analytical overlay information generated by the arthroscopic video analysis apparatus 825. In one example, the processed arthroscopic video data 940 represents a final combined video and/or data stream containing real-time processed full resolution endoscopic video with superimposed analytical data.

[0181] While the arthroscopic video analysis system 820 is illustrated in this example as including a single device, the arthroscopic video analysis system 820 in other examples can include a plurality of devices each having one or more processors (each processor with one or more processing cores) that implement one or more steps of this technology. In these examples, one or more of the devices can have a dedicated communication interface or memory. Alternatively, one or more of the devices can utilize the memory, communication interface, or other hardware or software components of one or more other devices included in the arthroscopic

video analysis system 820. Additionally, one or more of the devices that together comprise the arthroscopic video analysis system 820 (e.g., the arthroscopic video processing apparatus 825) in other examples can be standalone devices or integrated with one or more other devices or apparatuses. In one example, one or more aspects of the arthroscopic video analysis system 820 can be performed by virtual devices.

[0182] One or more of the components depicted in the system 80, such as the arthroscopic video analysis system 820, for example, may be configured to operate as virtual instances on the same physical machine. In other words, the arthroscopic video analysis system 820 may operate on the same physical device rather than as separate devices communicating through connection(s) and/or communication network(s). Additionally, there may be more or fewer arthroscopic video analysis systems 820 than are illustrated in FIG. 8.

[0183] In addition, two or more computing systems or devices can be substituted for any one of the systems or devices in any example. Accordingly, principles and advantages of distributed processing, such as redundancy and replication also can be implemented, as desired, to increase the robustness and performance of the devices and systems of the examples.

[0184] The examples may also be embodied as one or more non-transitory computer readable media having instructions stored thereon for one or more aspects of the present technology, as described and illustrated by way of the examples herein. The instructions in some examples include executable code that, when executed by the one or more processor(s) 921 of the arthroscopic video analysis system 820, cause the processors to carry out steps necessary to implement the methods of the examples of this technology that are described and illustrated herein.

[0185] Referring more specifically to FIG. 11, a flowchart of an exemplary method for improved arthroscopic video analysis using post-operative video analysis is illustrated. In step 1100 in this example, the arthroscopic video analysis system 820 of the system 80 obtains the raw unprocessed arthroscopic video data 930 for an arthroscopic procedure. The arthroscopic video data 930 is captured by the arthroscopic camera 810 in this example, and communicated to the arthroscopic video analysis system 820. In some examples, the video data 930 may be communicated from the arthroscopic camera 810 to the arthroscopic video analysis system 820 via a direct connection or communication network(s) as described and illustrated in more detail herein.

[0186] While the arthroscopic camera 810, which is part of an endoscopic device in this example, can be operated manually, the device including arthroscopic camera 810 can, in another example, also be operated via a robotic arm 105A configured to position the device associated with the arthroscopic camera 810 with respect to an anatomical area of interest associated with the patient and the surgical procedure. Although illustrated as a separate step 1100 in FIG. 11, the arthroscopic video data 930 is obtained continuously in the examples described and illustrated herein. Accordingly, step 1100 can be performed in parallel with one or more of steps 1102-1108.

[0187] In step 1102, the arthroscopic video analysis system 820 applies one or more video pre-processing techniques to the arthroscopic video data to improve the quality of the output video display as described below. The arthroscopic video analysis system 820 can apply any known pre-processing techniques in this step. In other examples, the video pre-processing can be performed in the arthroscopic video analysis system 820. In one example, one or more field-programmable gate arrays can be used to perform the pre-processing in step 1102 in the arthroscopic video analysis system 820. In some examples, the one or more video pre-processing techniques can include removing irrelevant background and accentuating brighter contours and regions, for example. The second video data stream 932 is provided to the arthroscopic video analysis apparatus 825. In one example, the second video data stream 932 is downsampled to enable low latency processing through the arthroscopic video analysis apparatus 825. Deep and/or machine learning algorithms are used by the arthroscopic video processing apparatus 825 of the arthroscopic video analysis system 820 to clean the raw unprocessed arthroscopic video data 930. In particular, a machine learning algorithm for arthroscopic video processing can be trained using input arthroscopic video data and optimized based on feedback regarding modifications made to the arthroscopic video data to improve and/or clean the resulting video feed, optionally based on identified anatomical structures as discussed in more detail below. In yet other examples, other types of video pre-processing technique(s) can also be used

Exemplary Workflows

[0188] The exemplary method described above with respect to FIG. 11 can be used in a number of workflows. Referring to FIG. 12, in one example, the exemplary method is employed

for post-surgery processing of the arthroscopic video data 930. In this example, the arthroscopic camera 810 acquires the arthroscopic video data 930 during a surgical procedure. The arthroscopic video data 930 is provided to the arthroscopic video analysis system 820 for the video pre-processing performed in step 1102.

[0189] The pre-processed video feed is then output for display on one of the sync devices 870 during the surgery, although the video can be displayed on other devices. The pre-processed video feed is also stored, for example, in the memory 1156 of the arthroscopic video analysis apparatus 825 for post-operative processing, although the pre-processed video feed can be stored in other locations, for example cloud or local network devices 850.

[0190] The arthroscopic video analysis apparatus 825 then processes the data using one or more machine learning models as in step 1104 and generates the overlay information 933 as described in step 1106 of the exemplary method. In one example, the data is downsampled prior to the processing in step 1106. The arthroscopic video analysis system 820 then generates the processed arthroscopic video data 940 including a video feed having the one or more overlays of analytical information as described in step 1110 of the exemplary method. The videos containing the overlays are then stored, for example, in the memory 1156 of the arthroscopic video analysis apparatus 825, although the videos containing the overlays can be stored in other locations, such as cloud or local network devices 850.

[0191] The post-surgical processing workflow can be utilized, for example, to provide the videos containing the overlay information for playback as surgical training. Alternatively, the post-surgical processing workflow can be utilized for the billing procedures described above, in order to have video data including specific billing information obtained using machine learning without human intervention.

[0192] Referring now to FIG. 13, in another workflow, the exemplary method is employed for real-time video processing during a surgical procedure to provide real-time, contextual feedback to the surgeon or other relevant operators. In these examples, the arthroscopic camera 810 acquires the arthroscopic video data 930 during the surgical procedure. The arthroscopic video data 930 is provided to the arthroscopic video analysis system 820 for the video pre-processing performed in step 1102.

[0193] Next, the pre-processed video data is split, using a video splitter that can be part of the arthroscopic video analysis system 820 to provide two separate outputs. In one example, a

separate output is provided for the processing by the arthroscopic video analysis apparatus 825 using machine learning models as described in step 1104. The output for processing by the arthroscopic video analysis apparatus 825 can be down-sampled and compressed to provide a lower resolution for the processing step. This reduces the processing time to allow the feedback from the processing in step 1104 to be presented in real-time. In one example, the video data that is processed in step 1104 can have a resolution of 1080p or lower. The second output maintains the resolution of the arthroscopic camera 810, which in one example can be 4k resolution.

[0194] The arthroscopic video analysis apparatus 825 processes the down-sampled and compressed video data using one or more machine learning models, as described in step 1104 of the exemplary method, and generates one or more overlays of analytical information devoid of the low resolution video data, as described in step 1106 of the exemplary method.

[0195] Referring again to FIG. 13, the two video outputs may be merged to provide the overlays of analytical information obtained in step 1106, using alpha blending or a mask, to mix with the high resolution video stream as in step 1110 of the exemplary method. The combined video stream is output to one of the sync devices 870, such as a display device 125, or other display, to provide a video stream of the surgical procedure with an overlay of the analytical information obtained in step 1106. The video provides real-time, contextual feedback regarding the surgical procedure on the display device 125.

[0196] With this technology, video outputs of arthroscopic surgeries can be generated in which analytic information, based on real-time processing of the video feed, can be overlaid onto the video feed to provide real-time information regarding the procedure. This technology automatically recognizes and identifies anatomical structures of interest associated with the procedure, recognizes and identifies pathologies, and/or provides measurements of interest related to the surgical procedure. Continuous, real-time updating of collected arthroscopic video data allows for an improved contextual understanding of the surgical procedure using the enhanced video data. Additionally, the obtained video data can be utilized for training using the information output related to the surgical procedure, or for billing purposes to identify the anatomical structures implicated and products utilized during the procedure.

[0197] While various illustrative embodiments incorporating the principles of the present teachings have been disclosed, the present teachings are not limited to the disclosed

embodiments. Instead, this application is intended to cover any variations, uses, or adaptations of the present teachings and use its general principles. Further, this application is intended to cover such departures from the present disclosure that are within known or customary practice in the art to which these teachings pertain.

[0198] In the above detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the present disclosure are not meant to be limiting. Other embodiments may be used, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that various features of the present disclosure, as generally described herein, and illustrated in the Figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

[0199] The present disclosure is not to be limited in terms of the particular embodiments described in this application, which are intended as illustrations of various features. Many modifications and variations can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. Functionally equivalent methods and apparatuses within the scope of the disclosure, in addition to those enumerated herein, will be apparent to those skilled in the art from the foregoing descriptions. It is to be understood that this disclosure is not limited to particular methods, reagents, compounds, compositions or biological systems, which can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

[0200] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

[0201] It will be understood by those within the art that, in general, terms used herein are generally intended as "open" terms (for example, the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," et cetera). While various compositions, methods, and devices are described in terms of "comprising" various components

or steps (interpreted as meaning “including, but not limited to”), the compositions, methods, and devices can also “consist essentially of” or “consist of” the various components and steps, and such terminology should be interpreted as defining essentially closed-member groups.

[0202] In addition, even if a specific number is explicitly recited, those skilled in the art will recognize that such recitation should be interpreted to mean at least the recited number (for example, the bare recitation of "two recitations," without other modifiers, means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to “at least one of A, B, and C, et cetera” is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (for example, “a system having at least one of A, B, and C” would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, et cetera). In those instances where a convention analogous to “at least one of A, B, or C, et cetera” is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (for example, “a system having at least one of A, B, or C” would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, et cetera). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, sample embodiments, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase “A or B” will be understood to include the possibilities of “A” or “B” or “A and B.”

[0203] In addition, where features of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group.

[0204] As will be understood by one skilled in the art, for any and all purposes, such as in terms of providing a written description, all ranges disclosed herein also encompass any and all possible subranges and combinations of subranges thereof. Any listed range can be easily recognized as sufficiently describing and enabling the same range being broken down into at least equal halves, thirds, quarters, fifths, tenths, et cetera. As a non-limiting example, each range discussed herein can be readily broken down into a lower third, middle third and upper third, et cetera. As will also be understood by one skilled in the art all language such as “up to,” “at

least," and the like include the number recited and refer to ranges that can be subsequently broken down into subranges as discussed above. Finally, as will be understood by one skilled in the art, a range includes each individual member. Thus, for example, a group having 1-3 components refers to groups having 1, 2, or 3 components. Similarly, a group having 1-5 components refers to groups having 1, 2, 3, 4, or 5 components, and so forth.

[0205] The term "about," as used herein, refers to variations in a numerical quantity that can occur, for example, through measuring or handling procedures in the real world; through inadvertent error in these procedures; through differences in the manufacture, source, or purity of compositions or reagents; and the like. Typically, the term "about" as used herein means greater or lesser than the value or range of values stated by 1/10 of the stated values, e.g., ±10%. The term "about" also refers to variations that would be recognized by one skilled in the art as being equivalent so long as such variations do not encompass known values practiced by the prior art. Each value or range of values preceded by the term "about" is also intended to encompass the embodiment of the stated absolute value or range of values. Whether or not modified by the term "about," quantitative values recited in the present disclosure include equivalents to the recited values, e.g., variations in the numerical quantity of such values that can occur, but would be recognized to be equivalents by a person skilled in the art.

[0206] Various of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art, each of which is also intended to be encompassed by the disclosed embodiments.

What is claimed is:

1. A method for analyzing surgical video data, the method comprising:

obtaining, by a video data analysis system, video data for a surgical procedure from a camera configured to capture the video data, wherein the video data comprises a field of view of an anatomical region;

generating, by the video data analysis system, a first video data stream and a second video data stream;

applying, by a video data analysis computing device of the video data analysis system, one or more machine learning models to the second video stream;

generating, by the video data analysis computing device of the video data analysis system, analytical information related to the anatomical region based on the applied machine learning models; and

associating, by the video data analysis system, the analytical information with the first video data stream.

2. The method of claim 1, further comprising:

outputting, by the video data analysis computing device of the video data analysis system, one or more overlays containing the analytical information;

correlating, by the video data analysis system, the one or more overlays to locations in the anatomical region related to the analytical information; and

generating, by the video data analysis system, a merged video feed data including the one or more overlays located at the correlated locations in the anatomical region on the first video data stream.

3. The method of claim 1, wherein the surgical procedure comprises an arthroscopic surgical procedure.

4. The method of claim 1, wherein the camera is located on an endoscopic device.

5. The method of claim 1, wherein the analytical information comprises an identification of one or more anatomical structures in the field of view of the anatomical region, an identification

of pathologies or defects in the anatomical region, identification of a surgical tool used in the surgical procedure, a location or type of an implant in the anatomical region, a state of the surgical procedure, or one or more geometrical measurements related to anatomical structures in the field of view of the anatomical region.

6. The method of claim 1, wherein the analytical information comprises a bitmask corresponding to one or more anatomical features in the field of view of the anatomical region.

7. The method of claim 1, further comprising:

displaying, by the video data analysis system, the first video data stream on a display interface, wherein the first video data stream is displayed without any overlays.

8. The method of claim 1, wherein generating the first video data stream further comprises, generating, by the video data analysis system, a first high-resolution, low-latency video data stream.

9. The method of claim 1, further comprising:

downsampling, by the video data analysis system, the second video stream prior to applying the one or more machine learning models.

10. The method of claim 1, further comprising:

outputting, by the video data analysis system, the merged video feed data for display on a display interface, wherein the merged video feed data is output in real-time.

11. A video data analysis system comprising:

a camera configured to capture video data;

a video data processing device comprising a first processor coupled to a memory and configured to execute programmed instructions stored in the first memory comprising:

obtaining video data for a surgical procedure, wherein the video data comprises a field of view of an anatomical region, and

generating a first video data stream and a second video data stream; and

a video data analysis computing device comprising a second processor coupled to a second memory and configured to execute programmed instructions stored in the second memory comprising:

applying one or more machine learning models to the second video stream, and

generating analytical information related to the anatomical region based on the applied machine learning models,

wherein the first processor is configured to execute at least one additional programmed instruction stored in the first memory comprising associating the analytical information with the first video data stream.

12. The system of claim 11, wherein the second processor is configured to execute at least one additional programmed instruction stored in the second memory comprising:

outputting one or more overlays containing the analytical information, and

correlating the one or more overlays to locations in the anatomical region related to the analytical information; and

wherein the first processor is configured to execute at least one additional programmed instruction stored in the first memory comprising generating merged video feed data including the one or more overlays located at the correlated locations in the anatomical region on the first video data stream.

13. The system of claim 11, wherein the surgical procedure comprises an arthroscopic surgical procedure.

14. The system of claim 11, wherein the camera is located on an endoscopic device.

15. The system of claim 11, wherein the analytical information comprises an identification of one or more anatomical structures in the field of view of the anatomical region, an identification of pathologies or defects in the anatomical region, identification of a surgical tool used in the surgical procedure, a location or type of an implant in the anatomical region, a state of the surgical procedure, or one or more geometrical measurements related to anatomical structures in the field of view of the anatomical region.

16. The system of claim 11, wherein the analytical information comprises a bitmask corresponding to one or more anatomical features in the field of view of the anatomical region.

17. The system of claim 11, further comprising:

a display interface,

wherein the first processor is configured to execute at least one additional programmed instruction stored in the first memory comprising displaying the first video data stream on the display interface,

wherein the first video data stream is displayed without any overlays.

18. The system of claim 1, wherein generating the first video data stream further comprises, generating, by the video data processing device, a first high-resolution, low-latency video data stream.

19. The system of claim 11, wherein the first processor is configured to execute at least one additional programmed instruction stored in the first memory comprising downsampling the second video stream prior to applying the one or more machine learning models.

20. The system of claim 11, further comprising:

a display interface,

wherein the first processor is configured to execute at least one additional programmed instruction stored in the first memory comprising outputting the merged video feed data for display on the display interface,

wherein the merged video feed data is output in real-time.

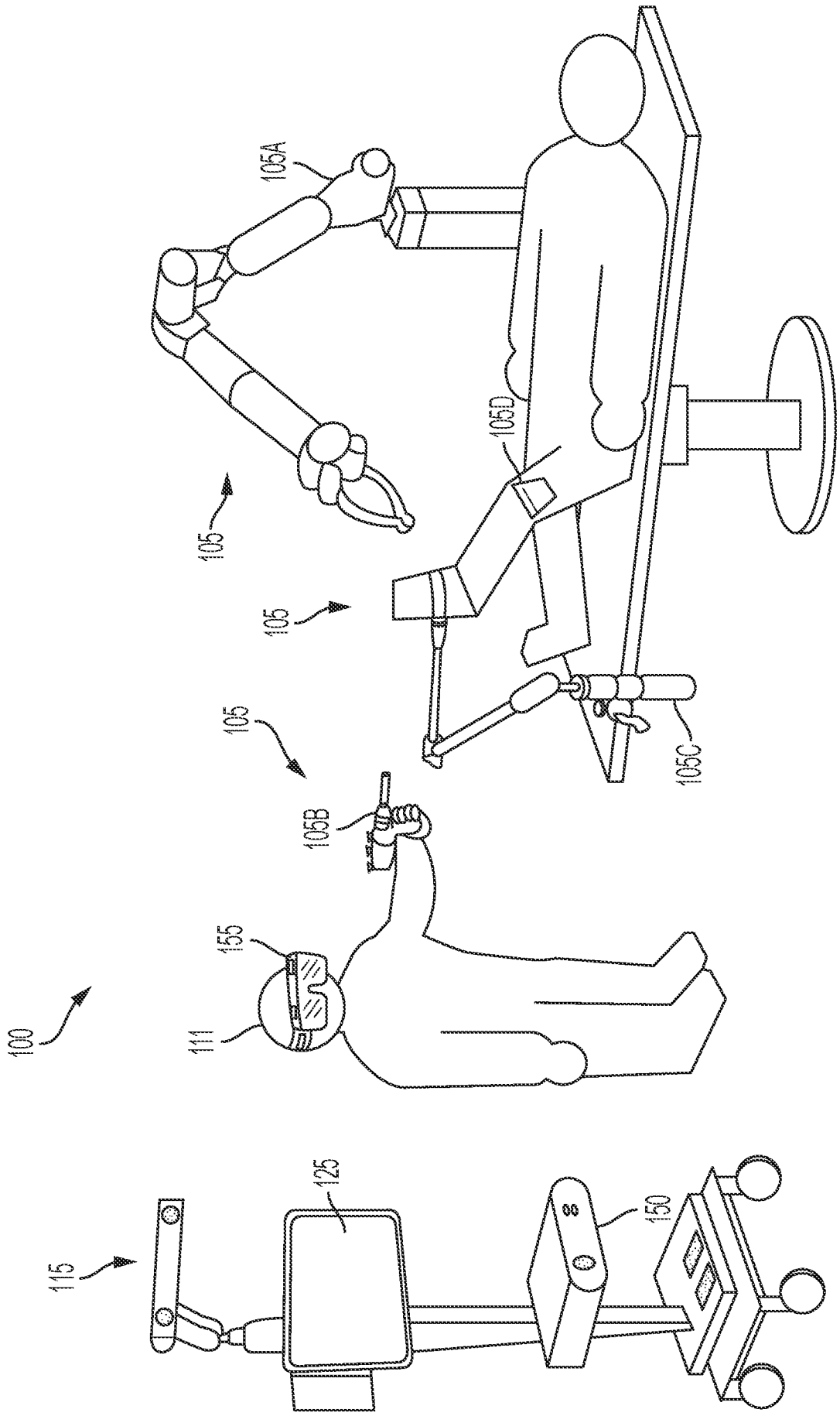


FIG. 1

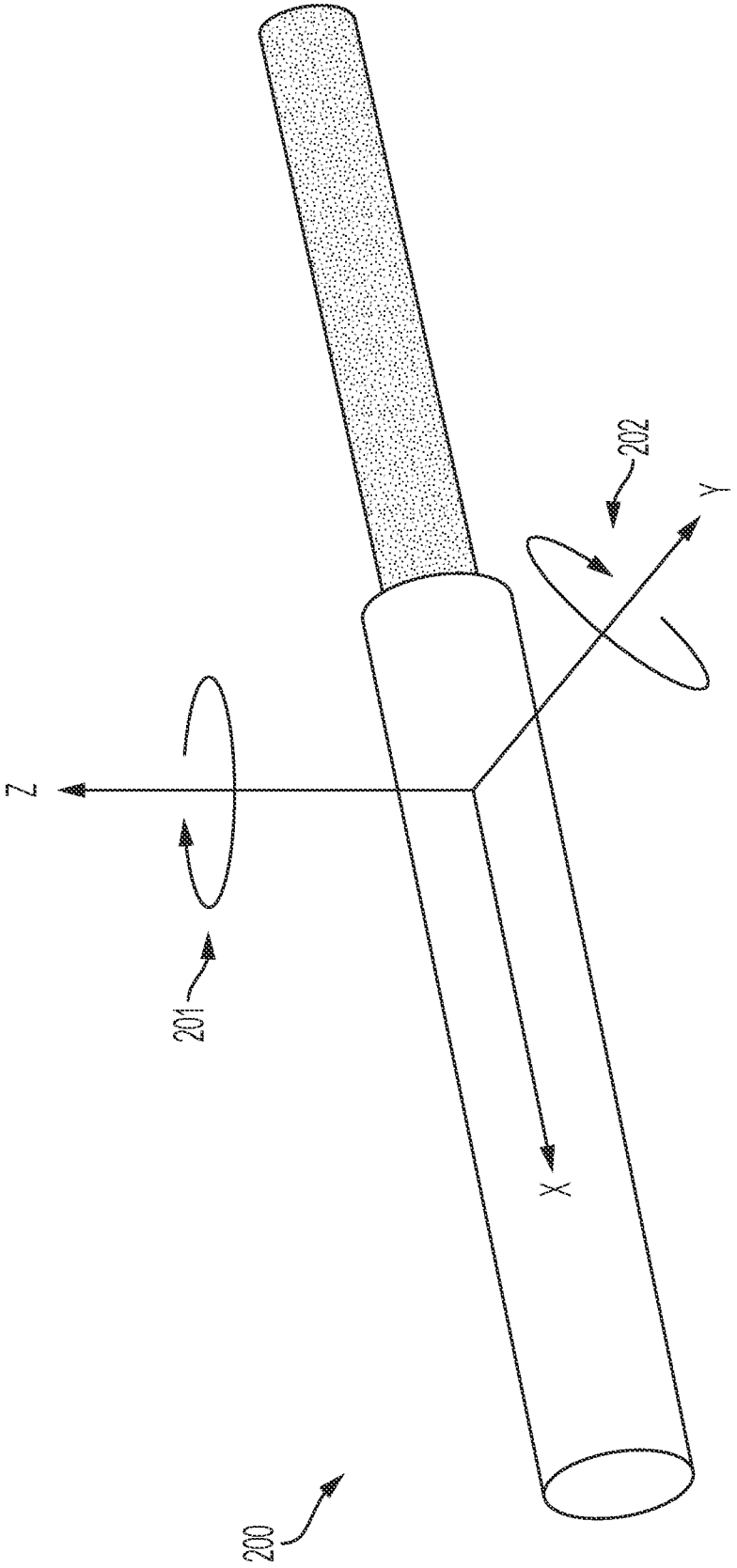


FIG. 2

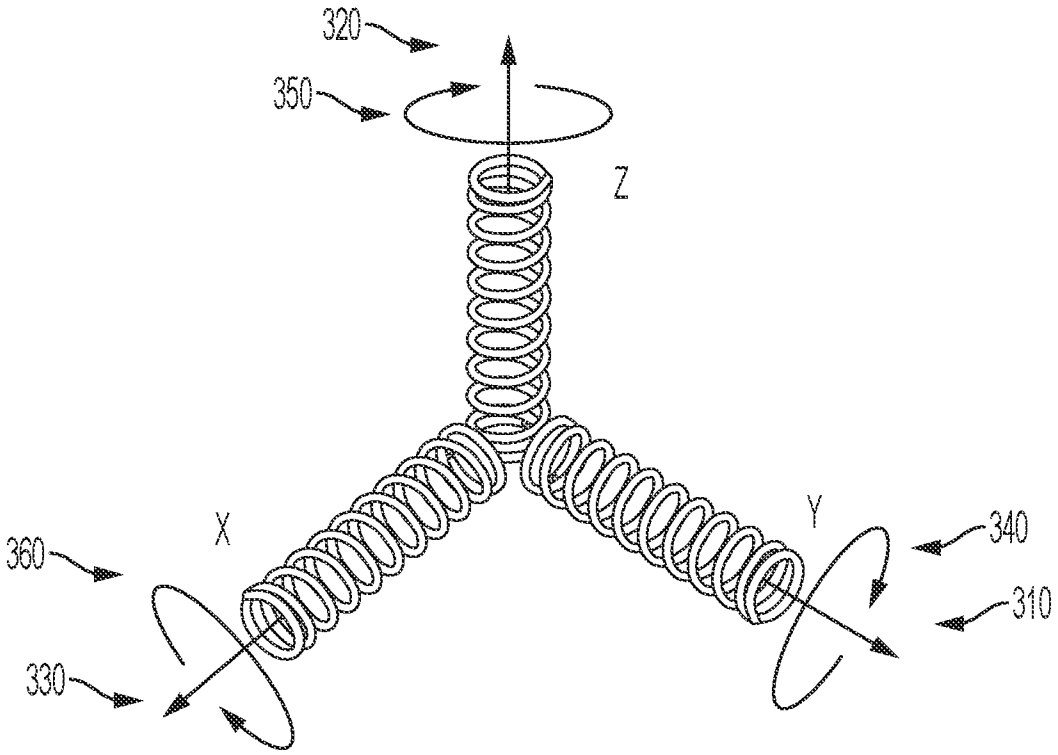


FIG. 3A

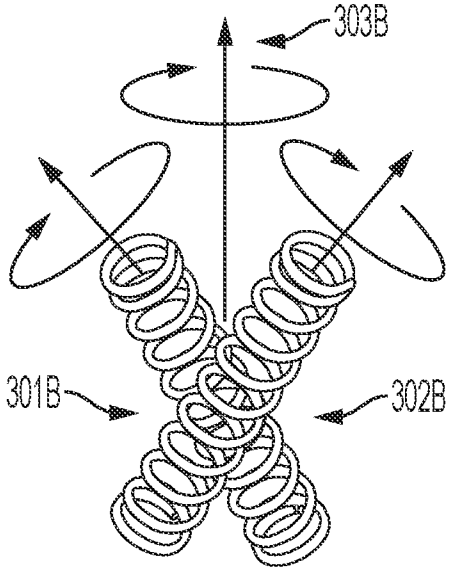


FIG. 3B

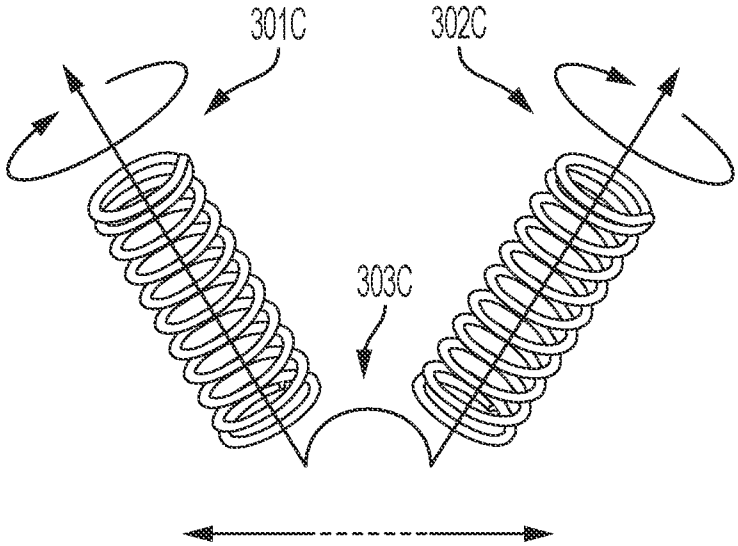


FIG. 3C

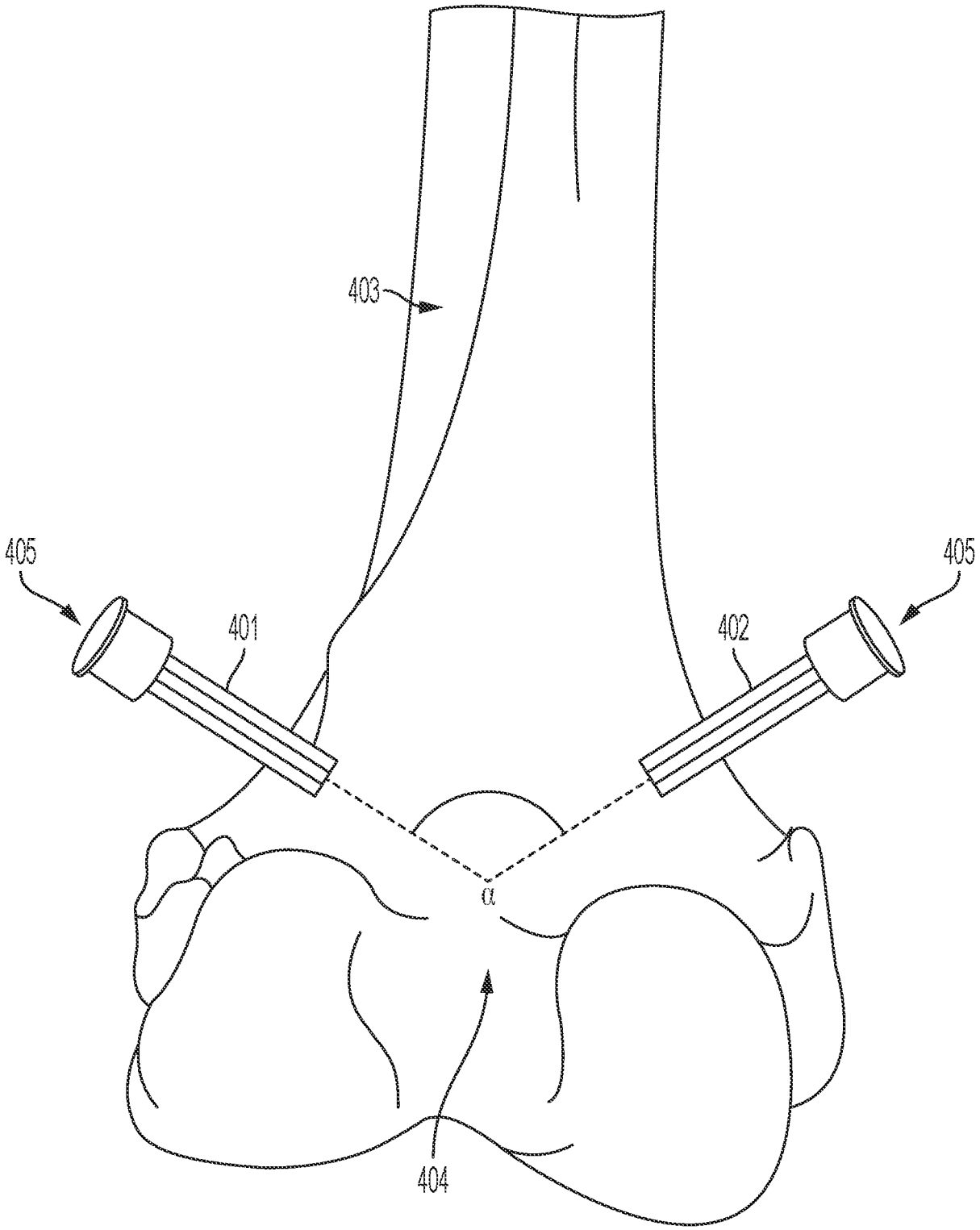


FIG. 4

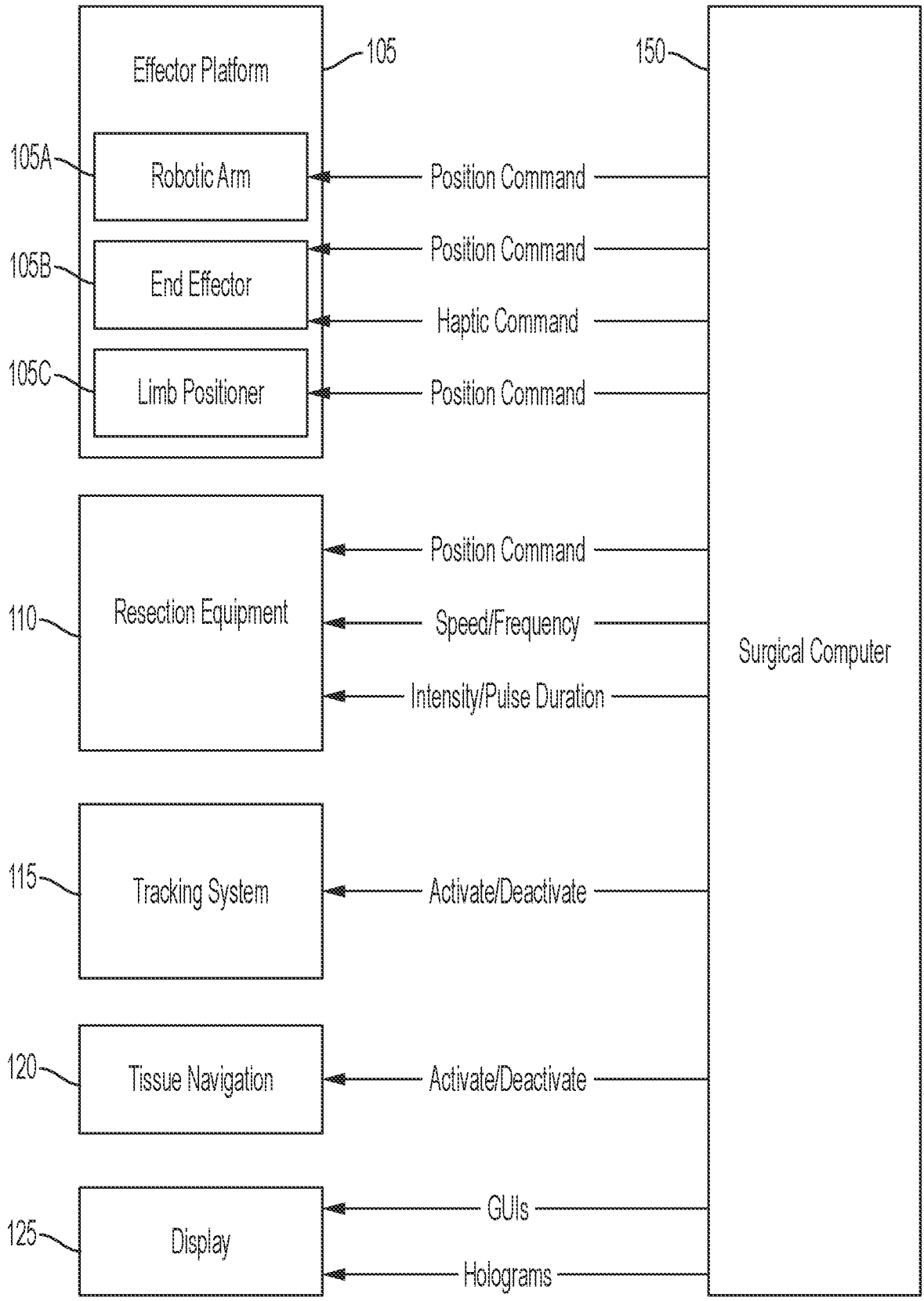

Effector Platform
105
150
105A
Robotic Arm
Position Command
105B
End Effector
Position Command
Haptic Command
105C
Limb Positioner
Position Command
110
Resection Equipment
Position Command
Speed/Frequency
Intensity/Pulse Duration
Surgical Computer
115
Tracking System
Activate/Deactivate
120
Tissue Navigation
Activate/Deactivate
125
Display
GUIs
Holograms

FIG. 5A

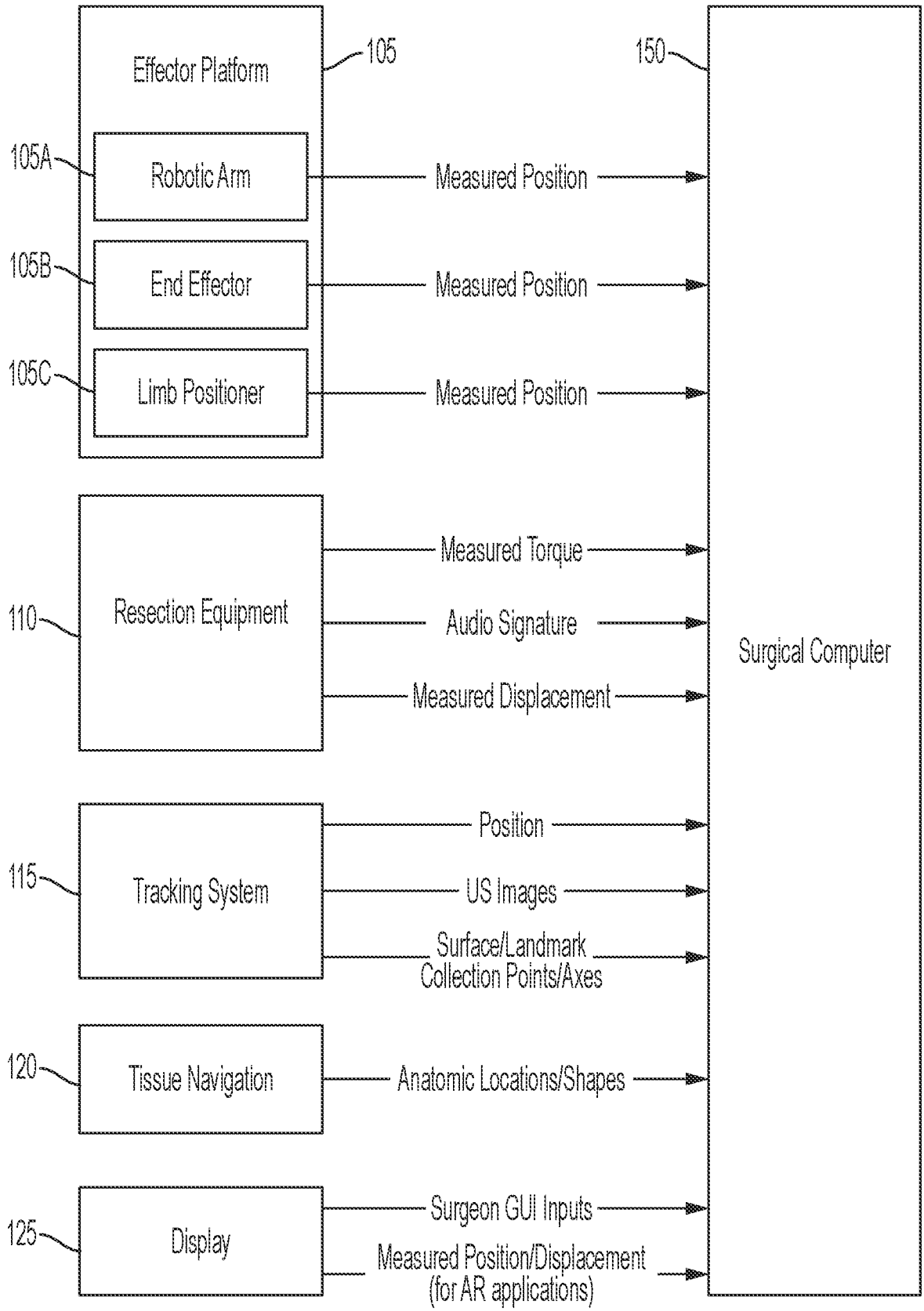

Effector Platform
105
150
105A
Robotic Arm
Measured Position
105B
End Effector
Measured Position
105C
Limb Positioner
Measured Position
Resection Equipment
110
Measured Torque
Audio Signature
Measured Displacement
Surgical Computer
Tracking System
115
Position
US Images
Surface/Landmark
Collection Points/Axes
Tissue Navigation
120
Anatomic Locations/Shapes
Display
125
Surgeon GUI Inputs
Measured Position/Displacement
(for AR applications)

FIG. 5B

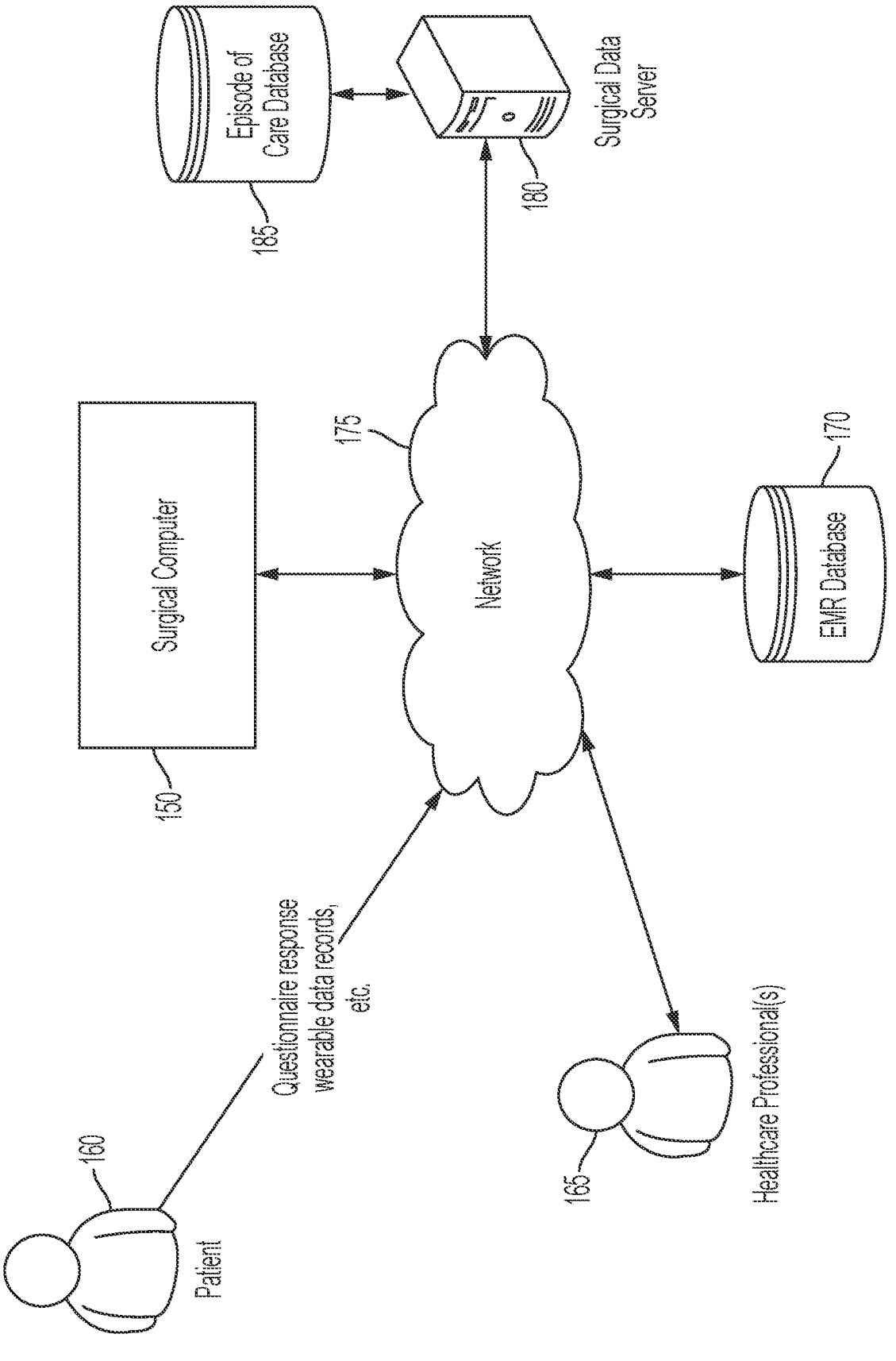

Episode of Care Database
185
Surgical Data Server
180
175
Network
Surgical Computer
150
EMR Database
170
Questionnaire response
wearable data records,
etc,
160
Patient
165
Healthcare Professional(s)

FIG. 5C

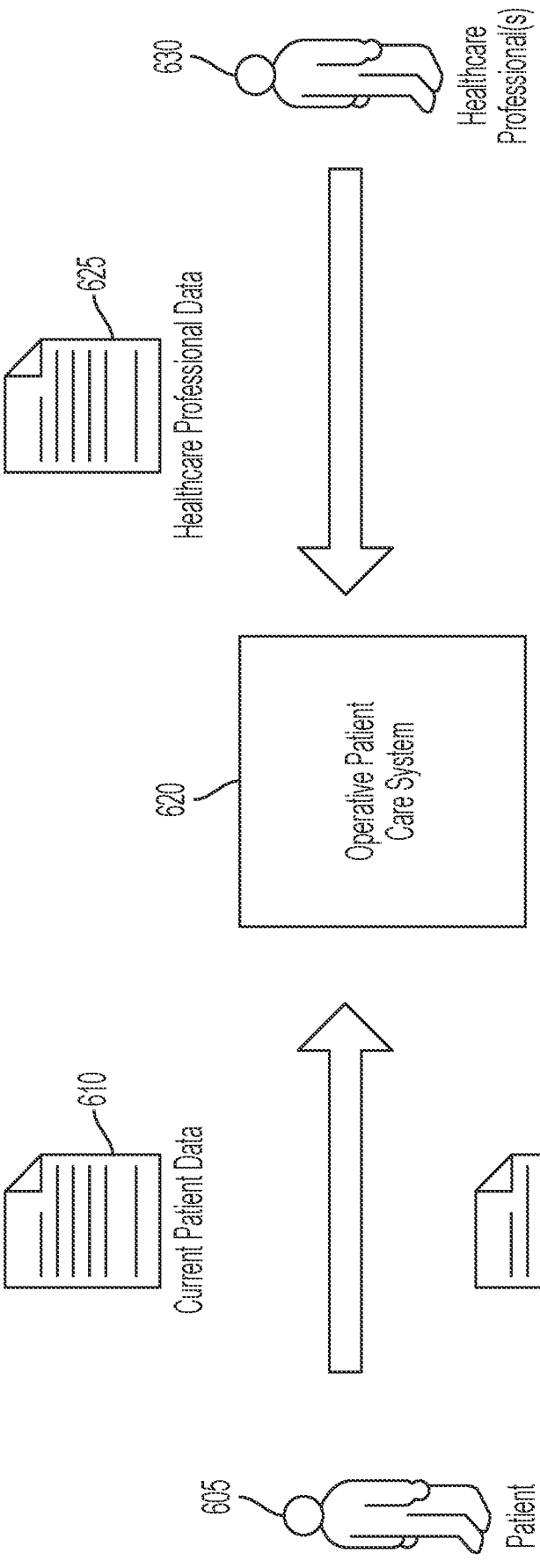

630
Healthcare Professional(s)
625
Healthcare Professional Data
620
Operative Patient Care System
610
Current Patient Data
615
Historical Patient Data
605
Patient

FIG. 6

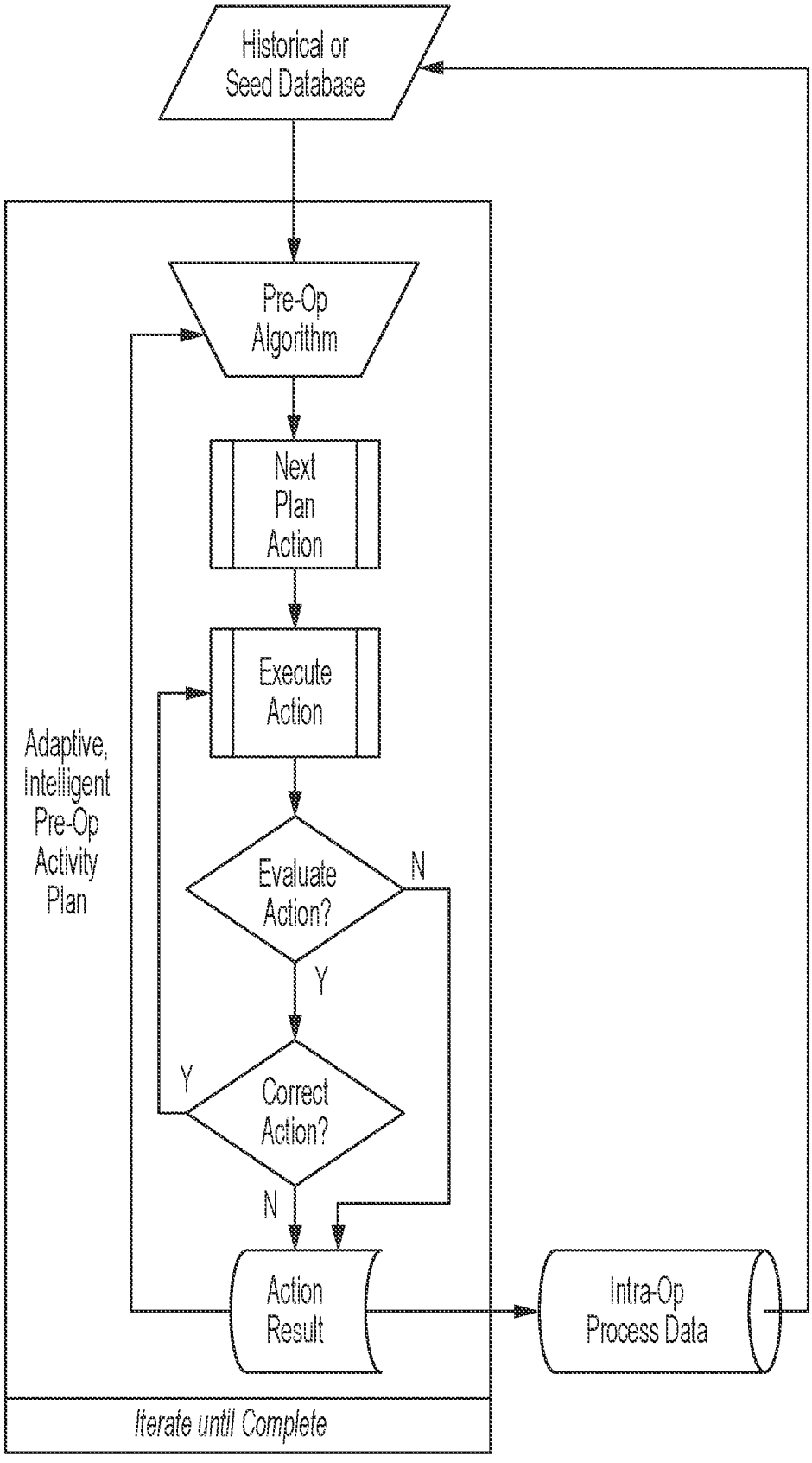

Historical or Seed Database
Pre-Op Algorithm
Next Plan Action
Execute Action
Evaluate Action?
N
Y
Correct Action?
Y
N
Action Result
Intra-Op Process Data
Adaptive, Intelligent Pre-Op Activity Plan
Iterate until Complete

FIG. 7A

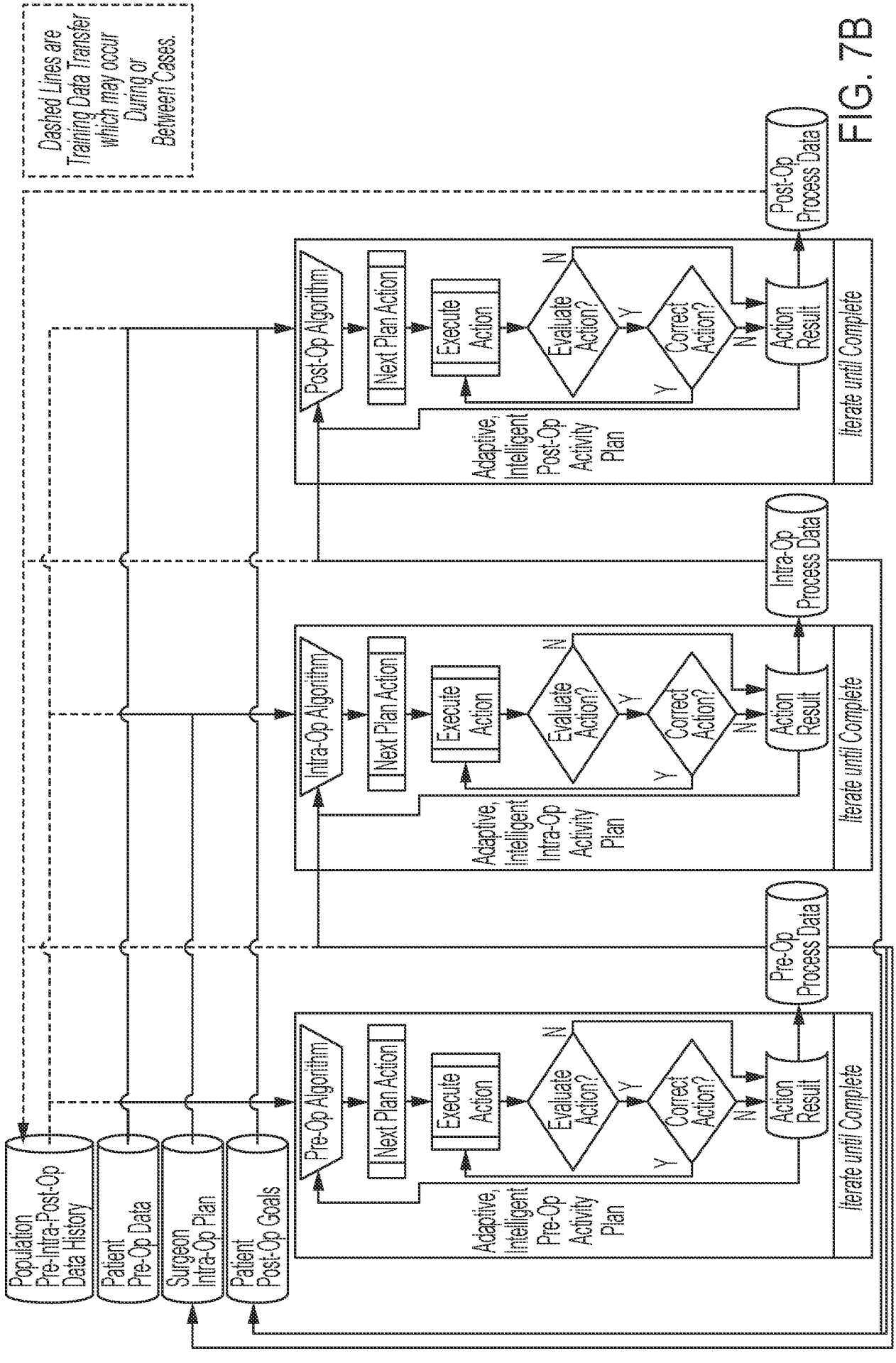

Dashed Lines are Training Data Transfer which may occur During or Between Cases.
Population Pre-Intra-Post-Op Data History
Patient Pre-Op Data
Surgeon Intra-Op Plan
Patient Post-Op Goals
Pre-Op Algorithm
Next Plan Action
Execute Action
Evaluate Action?
Correct Action?
Action Result
Pre-Op Process Data
Adaptive, Intelligent Pre-Op Activity Plan
Iterate until Complete
Intra-Op Algorithm
Next Plan Action
Execute Action
Evaluate Action?
Correct Action?
Action Result
Intra-Op Process Data
Adaptive, Intelligent Intra-Op Activity Plan
Iterate until Complete
Post-Op Algorithm
Next Plan Action
Execute Action
Evaluate Action?
Correct Action?
Action Result
Post-Op Process Data
Adaptive, Intelligent Post-Op Activity Plan
Iterate until Complete
Y
N

FIG. 7B

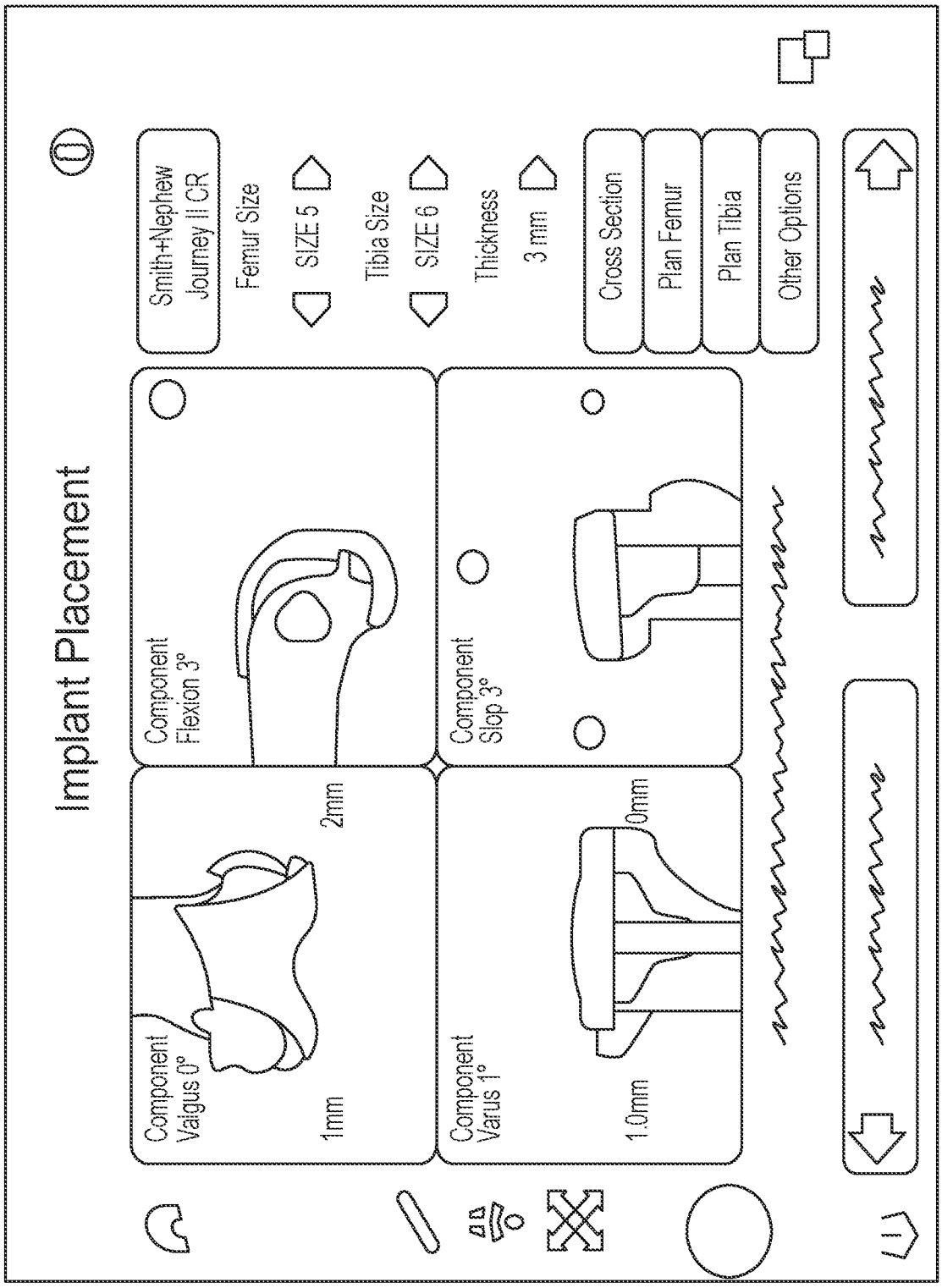

Implant Placement
Smith+Nephew Journey II CR
Femur Size
SIZE 5
Tibia Size
SIZE 6
Thickness
3 mm
Cross Section
Plan Femur
Plan Tibia
Other Options
Component Valgus 0°
1mm
Component Flexion 3°
2mm
Component Varus 1°
1.0mm
Component Slop 3°
0mm
T+0.5 minutes

FIG. 7C

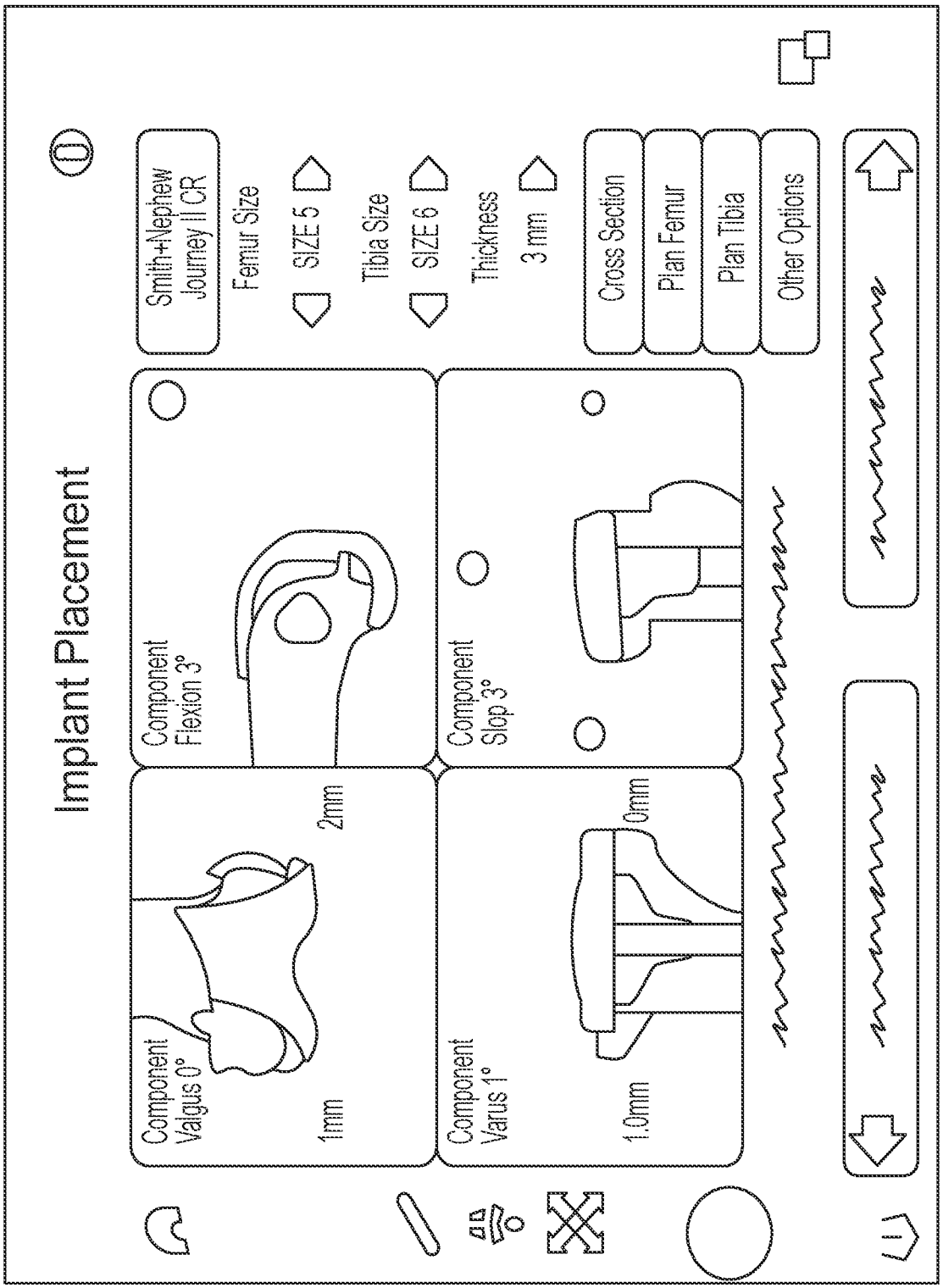


FIG. 7C CONTINUED

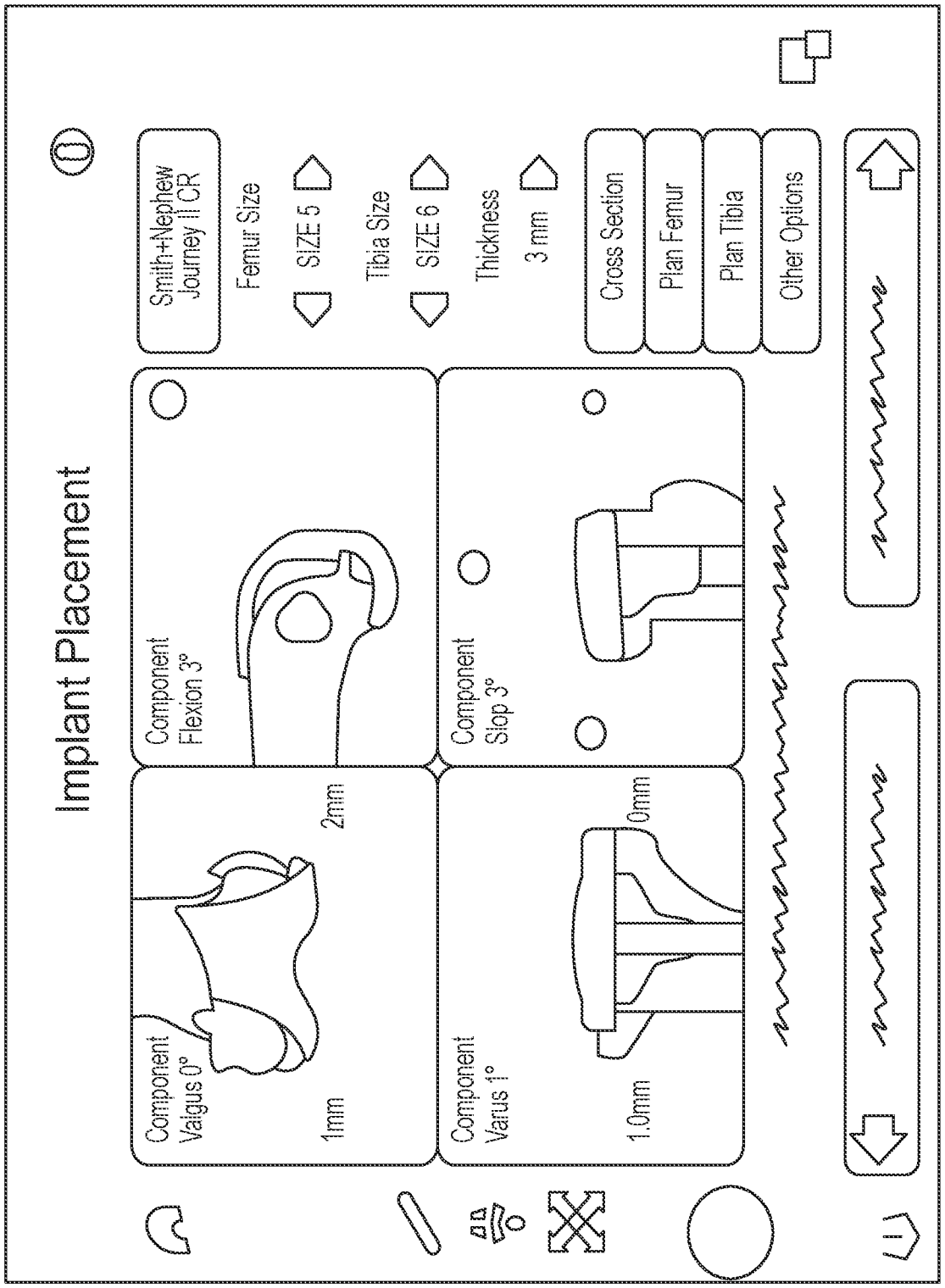


FIG. 7C CONTINUED

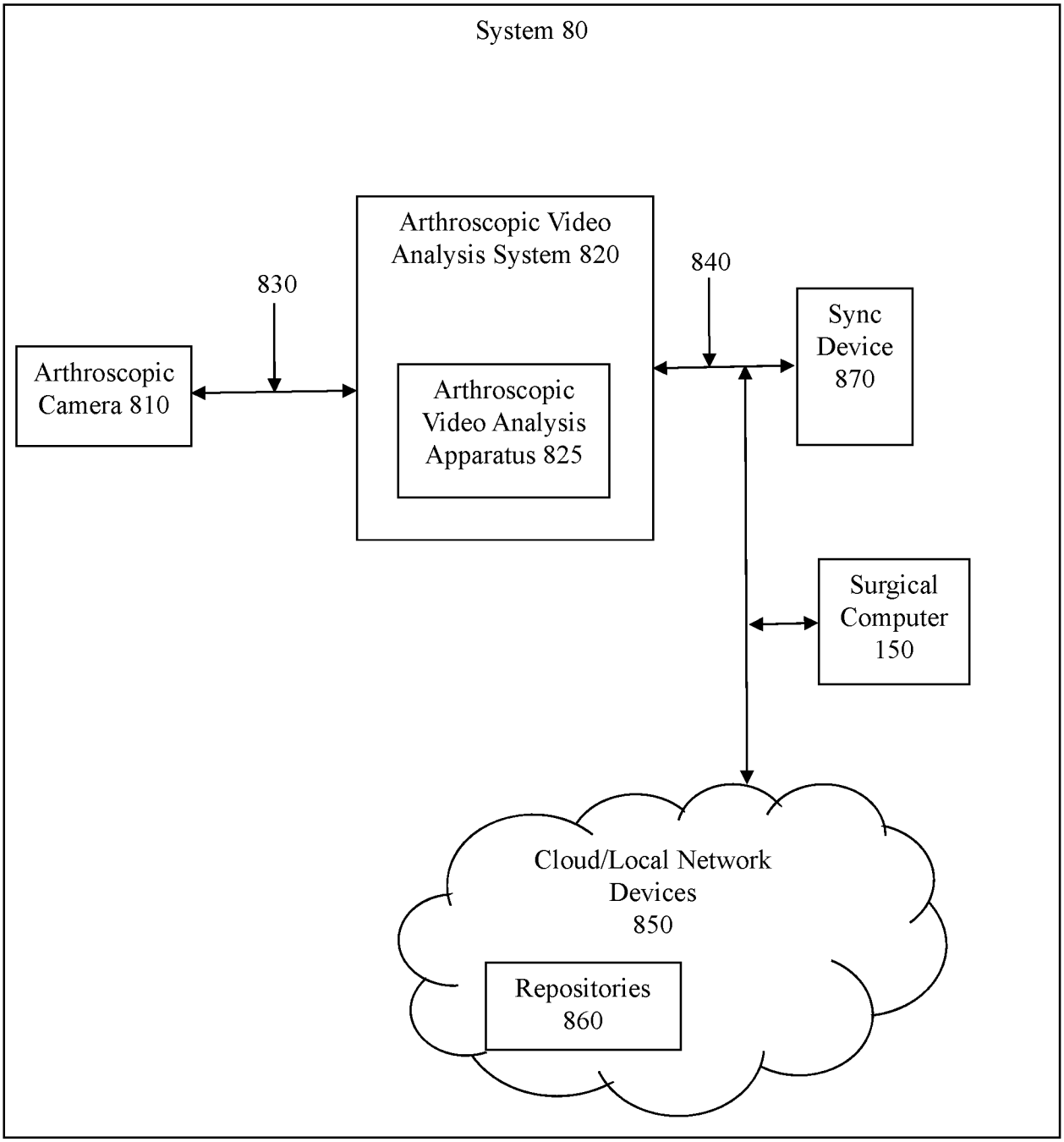

System 80
Arthroscopic Video Analysis System 820
830
840
Arthroscopic Camera 810
Arthroscopic Video Analysis Apparatus 825
Sync Device 870
Surgical Computer 150
Cloud/Local Network Devices 850
Repositories 860

FIG. 8

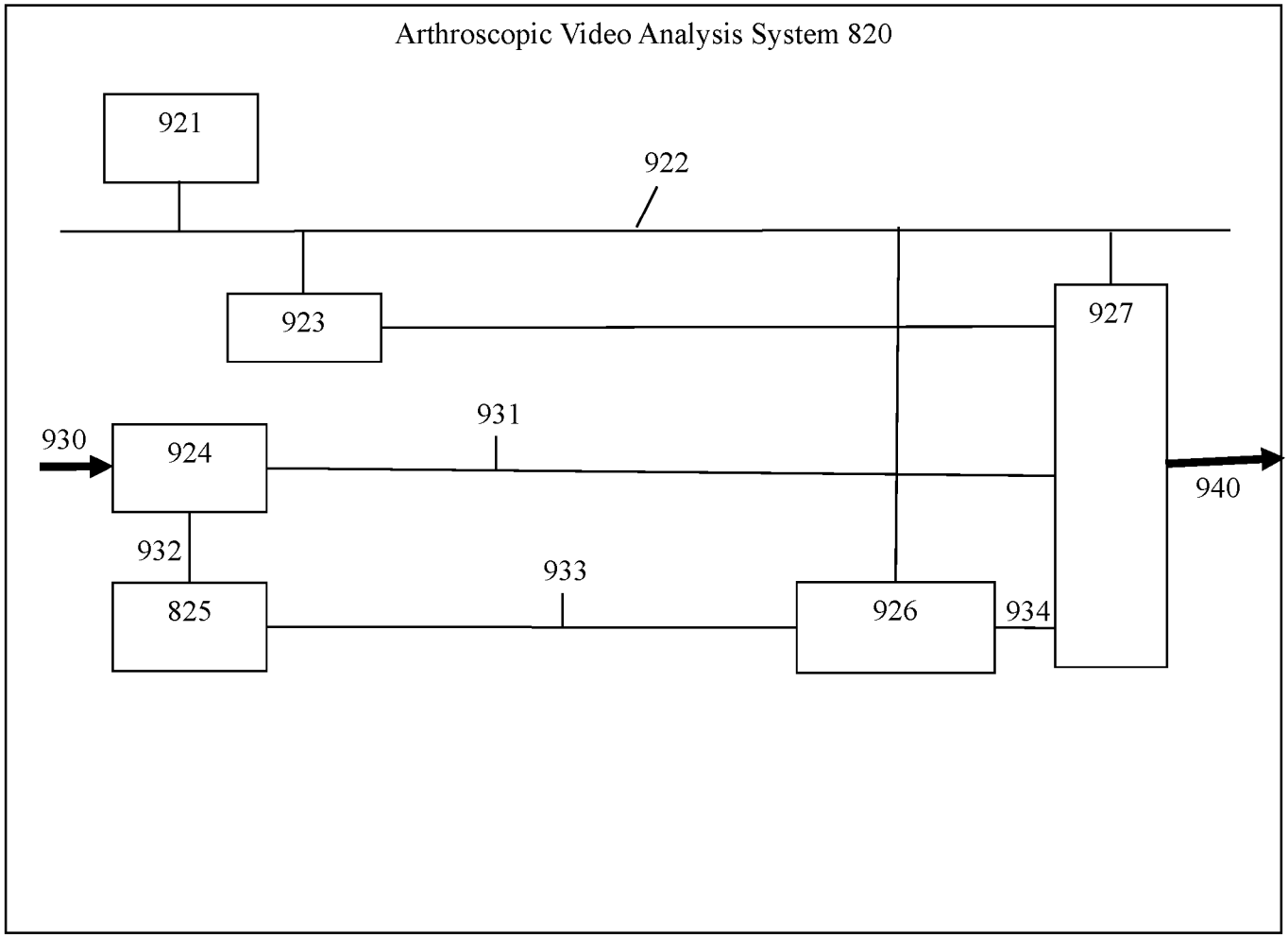

Arthroscopic Video Analysis System 820
921
922
923
927
930
924
931
940
932
933
825
926
934

FIG. 9

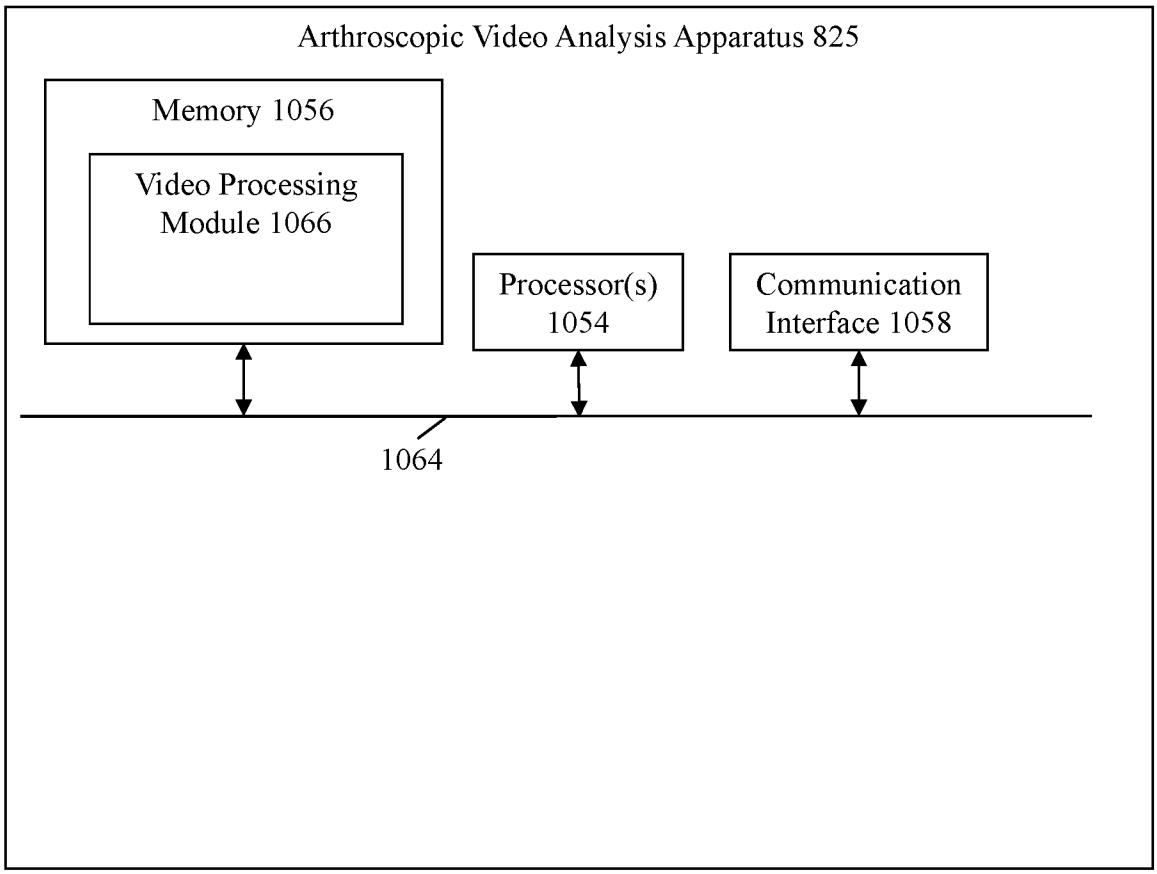

Arthroscopic Video Analysis Apparatus 825
Memory 1056
Video Processing Module 1066
Processor(s) 1054
Communication Interface 1058
1064

FIG. 10

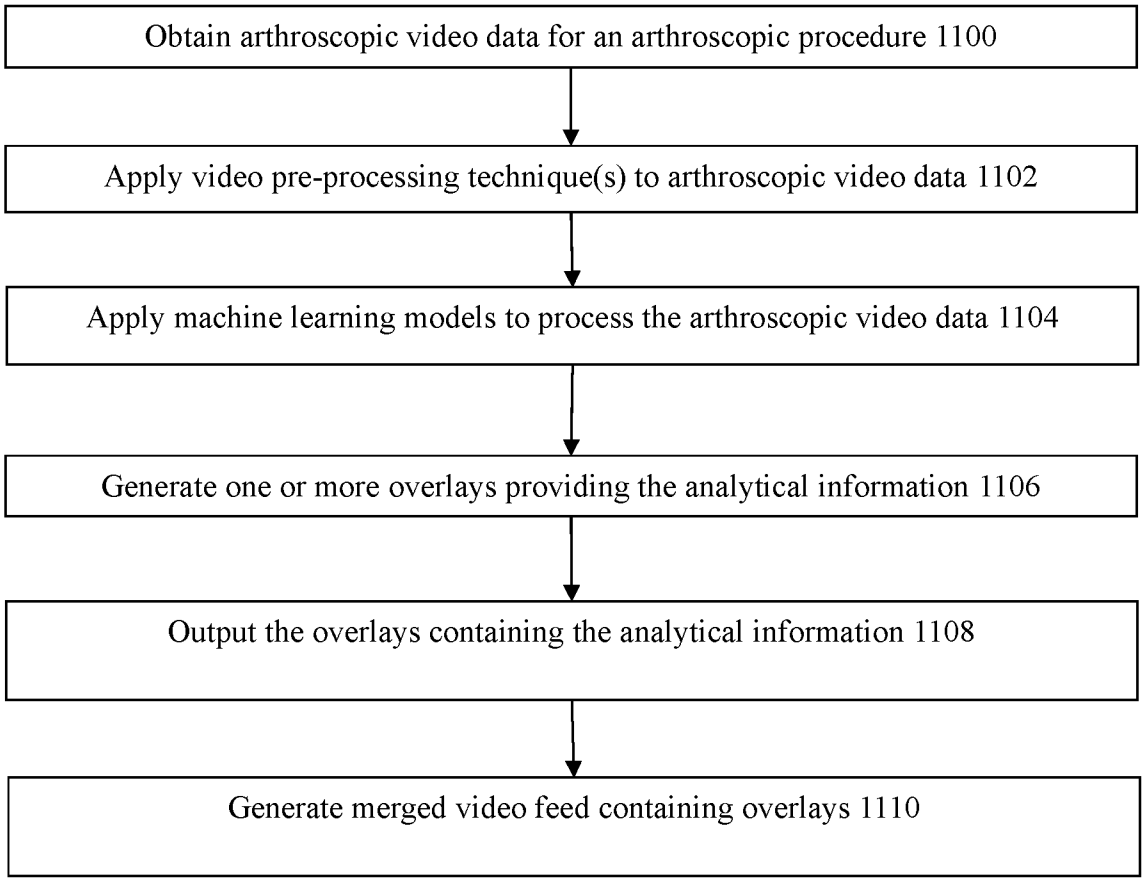

Obtain arthroscopic video data for an arthroscopic procedure 1100
Apply video pre-processing technique(s) to arthroscopic video data 1102
Apply machine learning models to process the arthroscopic video data 1104
Generate one or more overlays providing the analytical information 1106
Output the overlays containing the analytical information 1108
Generate merged video feed containing overlays 1110

FIG. 11

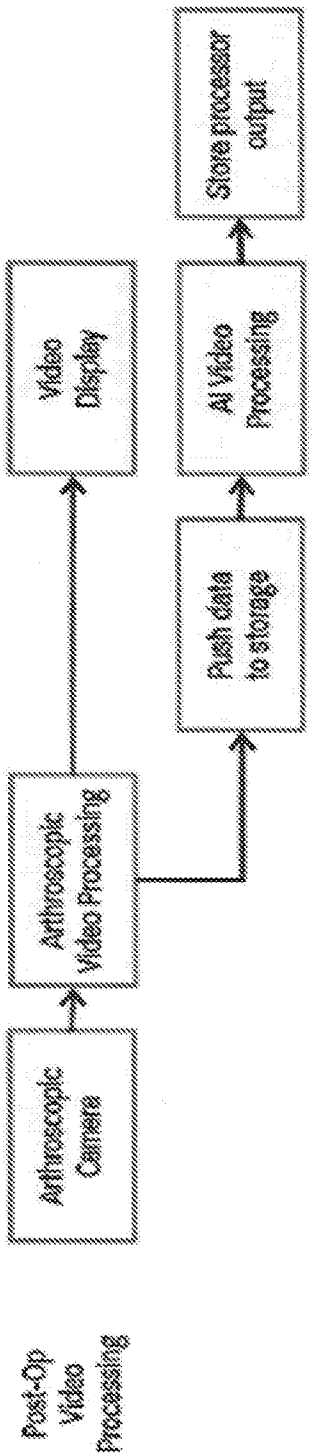

Post-Op Video Processing
Arthroscopic Camera
Arthroscopic Video Processing
Video Display
Push data to storage
AI Video Processing
Store processor output

FIG. 12

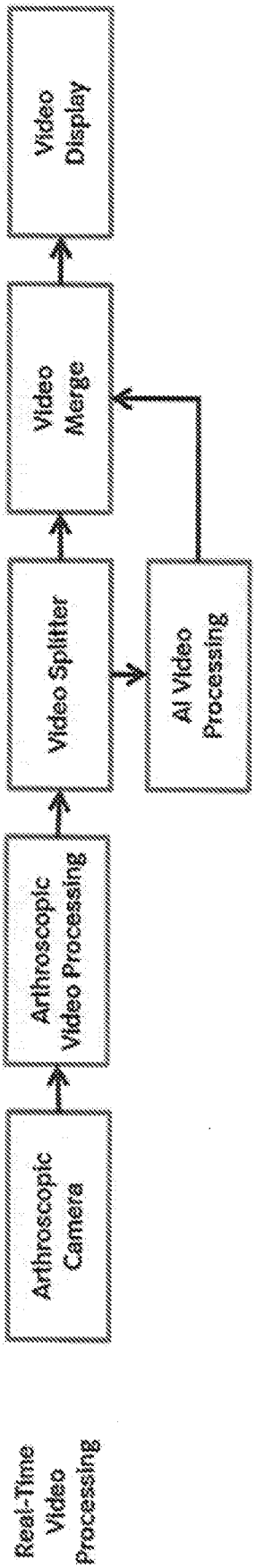

Real-Time Video Processing
Arthroscopic Camera
Arthroscopic Video Processing
Video Splitter
AI Video Processing
Video Merge
Video Display

FIG. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/019037

A. CLASSIFICATION OF SUBJECT MATTER
INV. G16H20/40 G16H30/40
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G16H H04N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2019/343588 A1 (JUERGENS THORSTEN [DE]) 14 November 2019 (2019-11-14) paragraph [0055] - paragraph [0062] -----	1-20
A	US 2019/310819 A1 (XU JIMMY [US] ET AL) 10 October 2019 (2019-10-10) paragraph [0054] paragraph [0053] -----	1-20
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19 May 2021	28/05/2021

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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