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COMPUTER ASSISTED SURGERY NAVIGATION MULTI-POSTURE IMAGING BASED KINEMATIC SPINE MODEL

Abstract

A surgical planning system is disclosed which provides computer assisted navigation for spinal surgery. The surgical planning system includes a computer platform operative to obtain images of at least two different postures of a patient's spine, and to measure displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine. The computer platform is further operative to estimate stiffness of the patient's spine based on the measurements of displacement, and to generate a patient-specific kinematic model of the patient's spine based on the estimated stiffness, and provides a surgical plan based on the patient-specific kinematic model of the patient's spine.

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Background/Summary

FIELD

[0001] The present disclosure relates to medical devices and systems, and more particularly, providing navigation information to surgeons and/or surgical robots for computer assisted navigation during spinal surgery.

BACKGROUND

[0002] There are a numerous types of spinal surgery procedures, including vertebroplasty and kyphoplasty, spinal laminectomy or spinal decompression, discectomy, foraminotomy, spinal fusion, and disk replacement. Patient satisfaction with the outcome of spinal surgery can depend upon the surgeon's expertise with best practices and use of rapidly emerging innovations in surgical procedures, new and customized implant designs, computer-assisted navigation, and surgical robot systems.

[0003] For example, the postoperative outcome for patient from spinal surgery can be improved through interoperative actions which incise, dissect, or otherwise disturb patient anatomy only to the extent defined by a surgical plan. Failure to do so may result in iatrogenic pathologies and unwanted complications. It is therefore beneficial to fully understand the biological components of the anatomy at a surgical site. Currently, preoperative and/or intraoperative imaging can be provided to surgeons to help navigate surgery procedures and enable more direct visualization of the intraoperative progress of the surgery. Image based navigation may be used in conjunction with robotic navigation to perform a surgical procedure. These navigation approaches can be subject to limitations which should be addressed to reduce unnecessary disturbance of patient anatomy during surgery on the spine.

SUMMARY

[0004] Some embodiments of the present disclosure are directed to a surgical planning system to provide computer assisted navigation for spinal surgery. The surgical planning system includes a computer platform that is operative to obtain images of at least two different postures of a patient's spine, and to measure displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine. The computer platform is further operative to estimate stiffness of the patient's spine based on the measurements of displacement, to generate a patient-specific kinematic model of the patient's spine based on the estimated stiffness, and to provide a surgical plan based on the patient-specific kinematic model of the patient's spine.

[0005] Some other embodiments are directed to corresponding methods by a surgical planning system to provide computer assisted navigation for spinal surgery. Some other embodiments are directed to corresponding computer program products for a surgical planning system to provide computer assisted navigation for spinal surgery.

[0006] Other surgical planning systems, methods, and computer program products according to embodiments will be or become apparent to one with skill in the art upon review of the following drawings and detailed description. It is intended that all such surgical planning systems, methods, and computer program products be included within this description, be within the scope of the present disclosure, and be protected by the accompanying claims. Moreover, it is intended that all embodiments disclosed herein can be implemented separately or combined in any way and/or combination.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The accompanying drawings, which are included to provide a further understanding of the disclosure and are incorporated in a constitute a part of this application, illustrate certain non-limiting embodiments of inventive concepts. In the drawings:

[0008] FIG. **1** illustrates computer operations that can be performed by a computer platform of a surgical planning system to provide computer assisted navigation for spinal surgery in accordance with some embodiments;

[0009] FIG. **2** illustrates more detailed example computer operations that can be performed by a computer platform for some of the operations illustrated in FIG. **1** in accordance with some embodiments;

[0010] FIG. **3** illustrates a navigated spinal surgery workflow which uses a surgical planning system configured in accordance with some embodiments;

[0011] FIG. **4** illustrates a block diagram of the surgical planning system with associated data flows during the preoperative, intraoperative, and postoperative stages, and shows surgical guidance being provided to user displays and to a robot surgery system in accordance with some embodiments;

[0012] FIG. **5** illustrates an operational flowchart for generating a spinal surgery plan based on processing preoperative patient data through a spine model, and for using intraoperative feedback data and/or postoperative feedback data to adapt or machine-train the spine model in accordance with some embodiments;

[0013] FIG. **6** illustrates an overhead view of a surgical system arranged during a surgical procedure in a surgical room which includes a camera tracking system for computer assisted navigation during surgery and which may further include a surgical robot for robotic assistance according to some embodiments;

[0014] FIG. **7** illustrates the camera tracking system and the surgical robot positioned relative to a patient according to some embodiments;

[0015] FIG. **8** further illustrates the camera tracking system and the surgical robot configured according to some embodiments; and

[0016] FIG. **9** illustrates a block diagram of a surgical system that includes an extended reality headset, a computer platform, imaging devices, and a surgical robot which are configured to operate according to some embodiments.

DETAILED DESCRIPTION

[0017] Inventive concepts will now be described more fully hereinafter with reference to the accompanying drawings, in which examples of embodiments of inventive concepts are shown. Inventive concepts may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of various present inventive concepts to those skilled in the art. It should also be noted that these embodiments are not mutually exclusive. Components from one embodiment may be tacitly assumed to be present or used in another embodiment.

[0018] Spine kinematics depend on a variety of parameters including patients' age, sex, anatomy and pathological conditions. The biomechanical and geometrical properties of spine govern the kinematics and are needed for biomechanical modeling and predictive surgical planning. Although innovative surgical tools and robotic navigation have significantly improved the outcome of spine surgery, mechanical failure rate should continue to be improved.

[0019] In accordance with various presently disclosed embodiments, a surgical plan is adapted based on the patient's diagnosis and demographics, and moreover adapted based on prediction of

the postop alignment and overall outcome of the surgery. Understanding the stiffness of the spine during preoperative planning is a key constraint to achieving desired improvements but has previously been difficult to determine. The fundamental biomechanics of soft tissue are complicated in nature and are usually tested in cadavers or ex vivo tissues. Independent studies have typically lacked the ability to encompass a sufficiently relevant spectrum of patient variations and employ diverse methodologies, leading to challenges to conducting a meta-analysis.

[0020] The present disclosure provides operational embodiments that analyze multimodal patient images and/or multi-posture patient images which can be obtained through a uniform operational workflow of imaging guidelines and processes. Computer operations estimate the flexibility and anatomical features of a patient's spine from inputted spine images of the patient at different defined postures. Computer operations correlate stiffness of the spine with flexibility, and further use information from biomechanical studies to extrapolate the results to generate or adapt a predicted surgically modified spine model. Computer operations construct a patient-specific kinematic model based on the stiffness and anatomical features of the spine. Using a surgeon's (or other user's) input fixation plan or other spine surgery plan, computer operations use the kinematic model to estimate the forces (e.g., force vectors and locations of force application) which need to be applied intraoperatively to achieve a certain postoperative correction of the spine.

[0021] These and other embodiments are initially discussed in the context of the example flowcharts of FIGS. **1** and **2**. FIG. **1** illustrates computer operations that can be performed by a computer platform of a surgical planning system to provide computer assisted navigation for spinal surgery. FIG. **2** illustrates more detailed example computer operations that can be performed by a computer platform for some of the operations illustrated in FIG. **1** in accordance with some embodiments.

[0022] Referring initially to FIG. **1**, operations by the computer platform include obtaining 150 images of at least two different postures of a patient's spine. The operations measure **152** displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine. The measurements may include measuring the displacement of vertebral body centers and intervertebral disc centers of the patient's spine between the images of the at least two different postures of the patient's spine. The operations estimate **154** stiffness of the patient's spine based on the measurements of displacement. The operations generate **156** a patient-specific kinematic model of the patient's spine based on the estimated stiffness, and generate **158** a surgical plan based on the patient-specific kinematic model of the patient's spine. The surgical plan may be used to provide computer assistance during pre-operative planning of surgery, used to provide navigation during surgery, and/or used to control a surgical robot during surgery, such as described in further detail below. The surgical plan may be recorded on paper and/or output as digital data that can be provided to a preoperative planning component, intraoperative guidance component, and/or other components as discussed below with regard to FIG. **3**.

[0023] As will be explained in further detail below, stiffness of the patient's spine is determined through the measurements of displacement of the anatomical features of the patient's spine as imaged in at least two different postures. The stiffness is then used to generate the patient-specific kinetic model which, in turn, is used to generate the surgical plan. As will be explained in detail below, the computer automated process can be applied more consistently across surgical plans for any patients to improve surgical outcomes, and can be adapted over time, e.g., through supervised machine learning from feedback, to more accurately generate patient-specific kinematic models.

[0024] Reference is now further made to the more detailed example operations shown in FIG. **2**. The images can be obtained from a set **250** of multi-posture images which can be from multi-modal imaging techniques and devices. Example multi-posture multi-modal images in the set **250** can include one or more of: a subset **251** of preoperative computerized tomography (CT) images and/or preoperative magnetic resonance imaging (MRI) images of the patient's spine in a supine posture; a

subset **252** of intraoperative CT and/or intraoperative fluoroscopy images of the patient's spine in a prone posture and/or lateral posture; a subset **253** of x-ray images and/or EOS (low-dose, weight-bearing X-ray) images of the patient's spine in a standing posture; and/or a subset **254** of other imaging modalities which may include x-ray and/or EOS images of the patient's spine in a bending posture, a flexion posture, and/or extension posture.

[0025] In some multi-image modality directed embodiments, the operation to measure **152** (FIG. **1**) and **255** (FIG. **2**) displacement of anatomical features of the patient's spine includes to measure the displacement of anatomical features of the patient's spine between images obtained by at least two different imaging modalities among a group of: CT imaging; MRI; Cone Beam Computerized Tomography (CBCT) imaging; Micro Computerized Tomography (MCT) imaging; 3D ultrasound imaging, x-ray imaging, and fluoroscopy imaging. The measured displacement may indicate distances that defined ones of the anatomical features have moved in a coordinate system of the 2D images or in 3D images and/or distances in another coordinate system (e.g., determined based on projecting the movements from the image coordinate system to other coordinate system).

[0026] The displacement measurements can indicate flexibility of each interverbal joint, and may be stratified by age, gender, etc.

[0027] In some multi-posture directed embodiments, the operation to measure **152** (FIG. **1**) and **255** (FIG. **2**) displacement of anatomical features of the patient's spine includes to measure the displacement of anatomical features of the patient's spine between at least two different ones of: a supine posture image of the patient's spine; a prone posture image of the patient's spine; a standing posture image of the patient's spine; a lateral posture image of the patient's spine; a standing posture image of the patient's spine; and a bending posture image of the patient's spine.

[0028] In a further embodiment, the measurement **152** (FIG. **1**) and **255** (FIG. **2**) of displacement of anatomical features of the patient's spine includes to measure the displacement of anatomical features of the patient's spine between a first image and a second image, where the first image is based on a preoperative CT or a preoperative MRI image of the patient's spine in one of a supine posture and a prone posture, and where the second image is based on an intraoperative CT image or an intraoperative fluoroscopy image of the patient's spine in the other one of the supine posture and the prone posture.

[0029] The measurement **152** (FIG. **1**) and **255** (FIG. **2**) of displacement of anatomical features of the patient's spine can include to measure the displacement of vertebral body centers and intervertebral disc centers of the patient's spine between the images of the at least two different postures of the patient's spine.

[0030] A 3D model of the patient's spine is generated **260** from any of the input image(s) by registration with a baseline spine model (e.g., statistical shape model of a spine). The same baseline spine model (e.g., statistical shape model) may be used for any of the imaging modalities, but may be adapted (tuned) using a registration algorithm based on characteristics of the particular imaging modality of the input image(s). This approach may ensure that the anatomical features of spine, including vertebral body centers, intervertebral disc centers, spinal processes, etc., are carried over to the patient-specific 3D spine model in a similar way for all imaging modalities.

[0031] Thus, in some embodiments, generation **260** of the 3D model of the patient's spine includes registering the anatomical features of the patient's spine imaged in at least one of the images to corresponding anatomical features of a baseline spine defined by a baseline spine model. The same baseline spine model may be used for all of the imaging modalities or the model may be selected from among a set of baseline spine models in a repository based on patient specific information (e.g., age, sex, etc.), based on similarity to the imaged anatomical features of the patient's spine to corresponding anatomical features of each of the baseline spine models, etc.

[0032] Flexibility of each intervertebral joint is estimated 255 based on the relative displacements in any two or more of the postures. Stiffness of intervertebral joint that governs the force displacement relationship is estimated 258 by correlating patient's spine flexibility (as indicated by

the measured displacement) with baseline parameters of spine stiffness **256**, which may be defined through biomechanical studies. The baseline parameters of spine stiffness **256** may define biomechanical relationships between the anatomical features of baseline spines (e.g., stiffness of intervertebral joints) measured through studies, e.g., cadavers, postoperative patient feedback, etc.) and may define modified spine stiffness parameters which are correlated to different defined surgical maneuvers of anatomical features of baseline spines. Operations for correlating the patient's spine flexibility with the baseline parameters of spine stiffness **256**, may include to correlate the patient's spine flexibility to one of a set of defined baseline parameters categories, where the set of baseline parameters categories may include baseline parameters for normal flexibility observed in studies, other baseline parameters for hypo-flexibility observed in studies, and still other baseline parameters for hyper-flexibility observed in studies.

[0033] A patient-specific kinematic model of the spine is generated **156** (FIG. **1**) and **262** (FIG. **2**) based on the stiffness estimate **258** for the patient's spine. In some embodiments, the patient-specific kinematic model is generated based on combining the 3D model of the patient's spine and the stiffness parameters. The patient-specific kinematic model is thereby adapted to the specific patient measured parameters, and is further adapted and used for a spine surgery plan for the patient as discussed below. Also as discussed below, the patient-specific kinematic model of the patient's spine can operationally define relationships between levels of force applied to anatomical features of the 3D model of the patient's spine to resulting displacement of the anatomical features, which can be used to determine **264** what displacements and corresponding forces are needed through the surgery plan to obtain certain corrective outcomes for the patient's spine.

[0034] In some embodiments, the operation to estimate **154** (FIG. **1**) and **258** (FIG. **2**) stiffness of the patient's spine based on the measurements of displacement, includes to determine flexibility of intervertebral joints of the patient's spine based on the measurements of displacement of the intervertebral joints of the patient's spine between the images of the at least two different postures of the patient's spine. The operations obtain baseline biomechanical stiffness parameters of corresponding intervertebral joints of a baseline spine defined by a baseline spine model, and then estimate the stiffness of the intervertebral joints of the patient's spine based on correlating the determined flexibility of the intervertebral joints of the patient's spine to the baseline biomechanical stiffness parameters of the corresponding intervertebral joints of the baseline spine defined by the baseline spine model.

[0035] In some further embodiments, the operation to generate **156** (FIG. **1**) and **262** (FIG. **2**) the patient-specific kinematic model of the patient's spine based on the estimated stiffness, includes to generate a 3D model of the patient's spine based on registering the anatomical features of the patient's spine imaged in at least one of the images to corresponding anatomical features of the baseline spine defined by the baseline spine model. The operations then generate the patient-specific kinematic model of the patient's spine using the estimate of the stiffness of the intervertebral joints of the patient's spine to operationally define relationships between levels of force applied to anatomical features of the 3D model of the patient's spine to resulting displacement of the anatomical features.

[0036] The surgical plan can then be generated **158** (FIG. **1**) and **264** (FIG. **2**) through operations that include to obtain a target displacement of at least one anatomical feature of the patient's spine, and estimate using the patient-specific kinematic model a level of force to be applied to at least one location on the patient's spine to obtain the target displacement of the at least one anatomical feature of the patient's spine. The surgical plan may be used to influence planning and/or actions by a surgeon and/or automated control of a computerized surgical process. For example, the surgical plan may be used to influence bending of a rod shape for spinal implant, selection of locations for spinal implants (e.g., screw placement, interbody spacer sizing and placement, etc.), osteotomy, etc.

[0037] Alternatively or additionally, the surgical plan can be generated **158** (FIG. **1**) and **264** (FIG. **2**) through operations that obtain a targeted displacement of anatomical features of the patient's

spine through fixation of an implant to the patient's spine, and estimate using the patient-specific kinematic model a level of force that will be exerted on a surgical implant when used to fixate anatomical features of the patient's spine at the targeted displacement.

[0038] An example of the force estimation can include to estimate a level of force exerted on a particular pedicle screw or other implant to secure a spine fixation implant to fixate anatomical features of the patient's spine at the targeted displacement defined by the surgical plan. Such force estimation can enable a surgeon to assess the risk of a pedicle screw or other implant being subjected to excessive force (stress) and becoming dislodged or loose if embedded according to a candidate surgical plan.

[0039] The patient-specific kinematic model of the patient's spine may be generated using a machine learning model, such as the machine learning model **400** of a machine learning processing circuit **316** which is described below with regarding to FIGS. **3** and **4**. In some embodiments, the operations to generate **156** (FIG. **1**) and **262** (FIG. **2**) the patient-specific kinematic model of the patient's spine based on the estimated stiffness, can include to process the images of the at least two different postures of the patient's spine through the machine learning model **400** of the machine learning processing circuit **316** (FIGS. **3** and **4**) to generate a function relating inputted levels of force to be applied to anatomical features of the patient's spine to outputted resulting displacement of the anatomical features. The machine learning model **400** is trained to relate displacement of intervertebral joints of spines between the images of the at least two different postures of the patient's spine to stiffness of the intervertebral joints of the patient's spine.

[0040] The computer platform can provide computer assisted navigation data (**158** in FIGS. **1** and **264** in FIG. **2**) based on the surgical plan to a display device for preoperative surgery planning and/or intraoperative assisted surgery navigation on the patient's spine. The process for intraoperative assisted surgery navigation can include operations to determine a target displacement of at least one anatomical feature of the patient's spine based on the surgical plan (**158** in FIGS. **1** and **264** in FIG. **2**). The operations can obtain tool tracking data indicating pose of a tool relative to the patient's spine, such as by using one or more of the processes described below with regard to FIGS. **6-8**, for tracking reference elements attached to tool(s) and other objects. The operations obtain spine tracking data indicating pose of the at least one anatomical feature of the patient's spine, e.g., using patient reference element(s) attached to the spine which are tracked by tracking cameras as discussed below. The operations process the tool tracking data, the spine tracking data, and the target displacement of the at least one anatomical feature of the patient's spine to generate intraoperative navigated guidance data. The operations can display the intraoperative navigated guidance data, e.g., on a head mounted display or other display device, to guide a user's movement of the tool.

[0041] Alternatively or additionally, the operations can provide computer assisted navigation data based on the surgical plan to a surgical robot **100** (FIGS. **6-8**) to control movement of an end-effector **112** (FIGS. **6-8**) of the surgical robot for computer assisted navigation during surgery on the patient's spine. The surgical navigation system can further include the surgical robot **100** which can be configured as shown in FIG. **7** to include a robot base **106**, a robot arm **104** connected between the robot base **106** and an end effector **112**. At least one motor is operatively connected to control movement of the end effector **112** via the robot arm **104** relative to the robot base **106**. The computer platform is further operative to determine a target displacement of at least one anatomical feature of the patient's spine based on the computer assisted navigation data. The computer platform obtains tool tracking data indicating pose of a tool relative to the patient's spine, and obtains spine tracking data indicating pose of the at least one anatomical feature of the patient's spine. The computer platform processes the tool tracking data, the spine tracking data, and the target displacement of the at least one anatomical feature of the patient's spine to generate intraoperative navigated guidance data. The computer platform controls movement of the at least one motor based on the intraoperative navigated guidance data to guide movement of the tool.

[0042] Example questions and problems that exist in current lumbar interbody fusion procedures and other spinal surgery procedures include: how to make surgical procedures be patient specific but also standardized across patients; what is the targeted correction needed for best patient outcome based on presentation; and how much direct decompression is needed versus how much indirect decompression is needed.

[0043] There are multiple technique combinations and solutions for the same patient presentation, and there is variance among surgeons on which technique or approach would be chosen for the best patient outcome. This results in some variation in actual patient outcomes.

[0044] Embodiments of the present disclosure can address various of these questions and problems, by streamlining planning and surgical workflows, and identifying and using correlations to standardize patient outcomes. Some embodiments are directed to using integrated spine models which may be generated or adapted using supervised machine learning from preoperative, intraoperative, and/or postoperative feedback.

[0045] Some embodiments of the present disclosure are directed to surgical planning systems for computer assisted navigation during spinal surgery. The system processes numerous different types of inputs and continued data collection using artificial intelligence through machine learning models to find correlations between different patient presentations and their outcomes, cause and effect of various spine surgery elements (direct vs indirect decompression and degree of either, different approaches, actual amount of correction achieved per technique and implants used, etc.) to continually optimize Al-assisted spine surgery plans for better patient outcomes.

[0046] To establish a spine model and predictive algorithm to further support surgeon decision making in lumbar interbody fusion surgery, and improve patient outcomes, data is needed from multiple sources as first an initial baseline, and then to continually update and improve the spine model with machine learning.

[0047] Key points and planes of anatomy (e.g. pedicle cross sections, canal perimeters, foraminal heights, facet joints, superior/inferior endplates, intervertebral discs, vertebral body landmarks, etc.) derived from specific patient image scans, are used to generate a segmented spine model that can be used to auto-calculate preoperative spinal alignment parameters. In addition, preoperative data collection from literature, studies, physician key opinion leaders, existing electronic health records can be combined with other data obtained from the patient's scans (e.g. bone density, spine stiffness, etc.) to compile all the factors for input to determine the best path forward in terms of surgical intervention. With these inputs and continually trained spine models, the system can draw correlations between patients and outcomes. Examples of data that can be collected as inputs and derived during the preoperative stages are discussed below.

[0048] The surgical planning systems include a computer platform that executes computer software to perform operations that can accurately detect key points of anatomy derived from specific patient scans. The computer platform may comprise one or more processors which may be connected to a same backplane, multiple interconnected backplanes, or distributed across networked platforms. The computer software may generate a segmented spine model that can be used to calculate preoperative spinal alignment parameters, and (through machine learning, anatomical standards, pre/intra/post-operative data collection, and known patient outcomes) generate a machine learning model that can provide predictive surgical outcomes for a defined patient.

[0049] The predictive surgical outcomes can have sufficient accuracy to be relied upon for determining or suggesting possible diagnoses and/or determining ideal surgery access approach(es), degree of decompression needed (indirect and/or direct), required interbody size/placement, custom interbody expansion set points (height and lordosis), and fixation type/size/placement that would be required for the most ideal spinal correction and patient outcomes. The need for this type of capability ranges from complex spinal deformity cases to single level degenerative spinal cases, e.g., Interlaminar Lumbar Instrumented Fusion (ILIF)

procedure, and may be beneficial for numerous types of spinal correction surgery including vertebral body replacements and disc replacements.

[0050] In some embodiments, the computer software accesses patient data in electronic health records (EHR) to operate to establish baseline data for a spine model for the patient. Patient data contained in an EHR may include, but is not limited to, patient demographics, patient medical history, diagnoses, medications, patient scans, lab results, and doctor's notes. The computer software may utilize machine learning model algorithms and operations for preoperative (preop) and/or intraoperative (intraop) surgical planning. These operations can reduce user input needed to set up patient profiles, and allow for continual seamless data synchronization.

[0051] This and other operational functionality can be provided by a surgical planning system for computer assisted navigation during spinal surgery. In accordance with some embodiments, the surgical planning system includes a computer platform that is operative to obtain intraoperative feedback data and/or postoperative feedback data regarding spinal surgery outcome for a plurality of patients, and to train a machine learning model based on the intraoperative feedback data and/or the postoperative feedback date. The computer platform is further operative to obtain preoperative patient data characterizing a spine of a defined-patient, generate a spinal surgery plan for the defined-patient based on processing the preoperative patient data through the machine learning model, and provide the spinal surgery plan to a display device for review by a user.

[0052] Elements of the computer platform which obtain the intraoperative feedback data and/or postoperative feedback data and which train the machine learning model may be the same as or different than elements of the computer platform which obtain the preoperative patient data, generate the spinal surgery plan, and provide the spinal surgery plan to the display device. The computer platform may include one or processors which execute software instructions in one or more memories and/or may include application specific integrated circuits. Multiple processors may be collocated and interconnected on a common substrate or common backplane or may be geographically distributed and communicatively connected through one or more local and/or wide-area communication networks.

[0053] Various embodiments disclosed herein are directed to improvements in operation of a surgical planning system providing navigated guidance when planning for and performing spinal surgical procedures, such as Interlaminar Lumbar Instrumented Fusion (ILIF) procedure, and spinal correction surgery which may include vertebral body replacement and/or disc replacement. A surgical planning system includes a machine learning model that can be adapted, trained, and configured to provide patient customized guidance during preoperative stage planning, intraoperative stage surgical procedures, and postoperative stage assessment. A database, e.g., centralized database, can store data that can be obtained in each of the stages across all patients who have previously used or are currently using the surgical planning system. In some embodiments, the machine learning model can be trained over time based on data from the database so that the patient customized guidance provides improved surgical outcomes.

[0054] Training of the machine learning model can include training based on learned correlations between patient data and surgical outcomes, correlations between cause and effect of various spine surgery elements including, for example, direct versus indirect spine decompression and amount (degree) of either, differences between spinal surgery techniques, actual amount of spinal correction achieved as a function of particular spinal surgery technique and surgical implants used, etc. Training of the machine learning model may be performed repetitively, e.g., continually when new data is obtained, in order to further improve surgical outcomes obtained by the spinal surgery plans generated from the machine learning model.

[0055] The machine learning model can use artificial intelligence techniques and may include a neural network model. The machine learning model may use centralized learning or federated learning techniques.

[0056] FIG. **3** illustrates a navigated spinal surgery workflow which uses a surgical planning

system **310** configured in accordance with some embodiments. Referring to FIG. **3**, three stages of workflow are illustrated: preoperative stage **300**; intraoperative stage **302**; and postoperative stage **304**. During the preoperative stage **300**, a user (e.g., surgeon) generates a surgical plan (case) based on analyzed patient images with assistance from the surgical planning system **310**. During the intraoperative stage **302**, the surgical planning system **310** uses a spinal surgery plan to provide navigated surgical assistance to the user, which may include displaying information and/or graphical indications to guide the user's actions, and/or provide instructions to guide a surgical robot for precise plan execution. During the postoperative stage **304**, postoperative feedback data characterizing surgery outcomes is collected by the surgical planning system **310**, such as by patient measurements and/or patient surveys, etc. Data obtained across all phases **300-304** can be stored in a central database **320** for use by the surgical planning system **310** to train a machine learning model of a machine learning processing circuit **316** (FIG. **4**). The machine learning model can include artificial intelligence (AI) processes, neural network components, etc. The machine learning model can be initially trained and then further trained over time to generate more optimal spinal surgery plans customized for patients that result in improved surgical outcomes. Further example types of data that can be collected during the preoperative stage **300**, intraoperative stage **302**, and postoperative stage **304** are discussed further below with regard to, e.g., FIG. **5**.

[0057] The example surgical planning system **310** shown in FIG. **3** includes a preoperative planning component **312**, an intraoperative guidance component **314**, a machine learning processing circuit **316**, and a feedback training component **410**.

[0058] As will be explained in further detail below regarding FIG. **4**, a feedback training component **410** is configured to obtain postoperative feedback data which may be provided by distributed networked computers regarding surgical outcomes for a plurality of patients, and to train a machine learning model based on the postoperative feedback data. Although FIG. **3** shows a single computer, e.g., smart phone, providing postoperative feedback data during the postoperative stage **304** through one or more networks **330** (e.g., public (Internet) networks and or private networks) to the surgical planning system **310** for storage in the central database **320**, it is to be understood that numerous network computers (e.g., hundreds of computers) could provide postoperative feedback data for each of many patients to the surgical planning system **310** (i.e., to the feedback training component **410**) for use in training the machine learning model. Moreover, as explained in further detail below, the feedback training component **410** can further train the machine learning model based on preoperative data obtained during the preoperative stage **300** for numerous patients and based on intraoperative data obtained during the intraoperative stage **302** for numerous patients. For example, the training can include adapting rules of a machine learning (e.g., artificial intelligence) algorithm, rules of one or more sets of decision operations, and/or weights and/or firing thresholds of nodes of a neural network model, to drive one or more defined key performance surgical outcomes indicated by the preoperative data and/or the intraoperative data toward one or more defined thresholds or other rule(s) being satisfied.

[0059] The preoperative planning component **312** obtains preoperative data from one or more computers which characterizes a defined-patient, and generates a spinal surgery plan for the defined-patient based on processing the pre-operative data through the machine learning model. The pre-operative planning component **312** provides the spinal surgery plan to a display device for review by a user. Accordingly, the preoperative planning component **312** of the machine learning processing circuit **316** generates a spinal surgery plan for a defined-patient using the machine learning model which has been trained based on the postoperative feedback data regarding surgical outcomes for the plurality of patients. The training of the machine learning model can be repeated as more postoperative feedback is obtained by the feedback training component **410** so that the spinal surgery plans that are generated will become more continuous improved at providing more optimal surgical outcomes for patients.

[0060] FIG. **4** illustrates a block diagram of the surgical planning system **310** with associated data

flows during the preoperative, intraoperative, and postoperative stages, and shows surgical guidance being provided to user displays and to a robot surgery system, configured in accordance with some embodiments.

[0061] Referring to FIG. **4**, the surgical planning system **310** includes the feedback training component **410**, the preoperative planning component **312**, and the intraoperative guidance component **314**. The surgical planning system **310** also includes machine learning processing circuit **316** that includes the machine learning model **400**, which may include an artificial intelligence and/or neural network component **402** as explained in further detail below.

[0062] The surgical planning system **310** contains a computing platform that is operative to obtain intraoperative feedback data and/or postoperative feedback data regarding spinal surgery outcome for a plurality of patients. A feedback training component **410** is operative to train the machine learning model **400** based on the intraoperative feedback data and/or the postoperative feedback data. The intraoperative feedback data and/or postoperative feedback data may also be stored in the central database **320**.

[0063] Preoperative patient data characterizing a spine of a defined-patient is obtained and may be preconditioned by a machine learning data preconditioning circuit **420**, e.g., weighted and/or filtered, before being processed through the machine learning model **400** to generate a spinal surgery plan for the defined-patient. The spinal surgery plan may be provided to a display device during preoperative planning. During surgery, the spinal surgery plan may be provided to XR headset(s) (also "head mounted display") worn by a surgeon and other operating room personnel and/or provide to other display devices to provide real-time navigated guidance to personnel according to the spinal surgery plan. Alternatively or additionally, the spinal surgery plan can be converted into instructions that guide movement of a robot surgery system, as will be described in further detail below.

[0064] The operation of the surgical planning system **310** to generate the spinal surgery plan may include to process the preoperative patient data through the machine learning model to identify predicted improvements to key points captured in medical images of the spine of the defined-patient, to output data indicating a planned access trajectory to access a target location on the spine of the defined-patient and/or data indicating a planned approach trajectory for implanting an implant device at the target location on the spine of the defined-patient, and/or to output data indicating at least one of: a planned implant location on the spine of the defined-patient; a planned size of an implant to be implanted on the spine of the defined-patient; and a planned interbody implant expansion parameter.

[0065] The operation of the surgical planning system **310** to generate the spinal surgery plan may include to process the preoperative patient data through the machine learning model to output data indicating planned amount of spine decompression to be surgically performed and/or indicating a planned amount of disc material of the spine to be surgically removed by a discectomy procedure.

[0066] The operation of the surgical planning system **310** to generate the spinal surgery plan may include to process the preoperative patient data through the machine learning model to output data indicating a planned curvature shape for a rod to be implanted during spinal fusion.

[0067] In some further embodiments, the surgical planning system **310** can be further operative to obtain defined-patient intraoperative feedback data that includes at least one of: data characterizing deviation between an intraoperative spinal surgery process performed on the defined-patient and the spinal surgery plan for the defined-patient; data characterizing deviation between an intraoperative access trajectory used to access a target location on the spine of the defined-patient and an access trajectory indicated by the spinal surgery plan for the defined-patient; and data characterizing deviation between an intraoperative approach trajectory used to implant an implant device at the target location on the spine of the defined-patient and an approach trajectory indicated by the spinal surgery plan for the defined-patient. The feedback training component **410** can be configured to train the machine learning model **400** based on the defined-patient intraoperative

feedback data.

[0068] In some further embodiments, the surgical planning system **310** can be further operative to obtain defined-patient intraoperative feedback data that includes at least one of: data characterizing an intraoperative measurement of amount of spine decompression obtained during spinal surgery according to the spinal surgery plan on the defined-patient; data characterizing an intraoperative measurement of amount of soft tissue disruption during spinal surgery according to the spinal surgery plan on the defined-patient; and data characterizing an intraoperative measurement of amount of disc material of the spine surgically removed by a discectomy procedure according to the spinal surgery plan on the defined-patient. The feedback training component **410** can be configured to train the machine learning model **400** based on the defined-patient intraoperative feedback data.

[0069] In some further embodiments, the surgical planning system **310** can be further operative to obtain defined-patient intraoperative feedback data that includes at least one of: data characterizing postoperative measurements of spine decompression captured in medical images of the spine of the defined-patient following spinal surgery; data characterizing postoperative measurements of spinal deformation captured in medical images of the spine of the defined-patient following spinal surgery; data characterizing postoperative measurements of amount of removed disc material of the spine captured in medical images of the spine of the defined-patient following the spinal surgery; and data characterizing postoperative measurements of amount of soft tissue disruption captured in medical images of the defined-patient following the spinal surgery. The feedback training component **410** can be configured to train the machine learning model **400** based on the defined-patient postoperative feedback data.

[0070] In some further embodiments, the surgical planning system **310** can be further operative to obtain defined-patient postoperative feedback data that includes at least one of: data characterizing implant failure following spinal surgery on the defined-patient; data characterizing bone failure following spinal surgery on the defined-patient; data characterizing bone fusion following spinal surgery on the defined-patient; and data characterizing patient reported outcome measures following spinal surgery on the defined-patient. The feedback training component **410** can be configured to train the machine learning model **400** based on the defined-patient postoperative feedback data.

[0071] The machine learning model **400** can include a neural network component **402** that includes an input layer having input nodes, a sequence of hidden layers each having a plurality of combining nodes, and an output layer having output nodes. At least one processing circuit (e.g., data preconditioning circuit **420**) can be configured to provide different entries of the intraoperative feedback data and/or the postoperative feedback data to different ones of the input nodes of the neural network component **402**, and to generate the spinal surgery plan based on output of output nodes of the neural network component **402**.

[0072] The feedback training component **410** may be configured to adapt weights and/or firing thresholds that are used by the combining nodes of the neural network component **402** based on values of the intraoperative feedback data and/or the postoperative feedback data.

[0073] A machine learning data preconditioning circuit **420** may be provided that pre-processes the obtained data, such as by providing normalization and/or weighting of the various types of obtained data, which is then provided to machine learning processing circuit **316** during a run-time phase or to the feedback training component **410** during a training phase for use in training the machine learning model **400**. In some embodiments, the training is performed continuously or at least occasionally during run-time.

[0074] A preoperative planning component **312** contains preoperative data from one of the distributed network computers characterizing a defined-patient, generates a spinal surgery plan for the defined-patient based on processing the preoperative data through the machine learning model **400**, and provides the spinal surgery plan to a display device for review by a user.

[0075] Thus, as explained above, the training can include adapting rules of an AI algorithm, rules of one or more sets of decision operations, and/or weights and/or firing thresholds of nodes of a neural network mode, to drive one or more defined key performance surgical outcomes indicated by the preoperative data and/or the intraoperative data toward one or more defined thresholds or other rule(s) being satisfied.

[0076] The machine learning model **400** can be configured to process the preoperative data to output the spinal surgery plan identifying an implant device, a pose for implantation of the implant device in the defined-patient, and a predicted postoperative performance metric for the defined-patient following the implantation of the implant device.

[0077] The machine learning model **400** can be further configured to generate the spinal surgery plan with identification of planned access trajectory to access a target location on the spine of the defined-patient and/or data indicating a planned approach trajectory for implanting an implant device at the target location on the spine of the defined-patient. A preoperative planning component **312** may provide data of the spinal surgery plan to a computer platform **900** (e.g., FIG. **9**) that allows review and modification of the plan by a surgeon. An intraoperative guidance component **314** may provide navigation information according to the spinal surgery plan to one or more display devices for viewing by a surgeon and/or other operating room personnel, e.g., to see-through display device **928** in an extended reality (XR) headset **140** (FIGS. **6** and **9**) for viewing as an overlay on the defined-patient. The intraoperative guidance component **314** may provide steering information to a robot controller of a surgical robot **100** (FIGS. **6-8**). The surgical robot **100** can include a robot base, a robot arm connected to the robot base and configured to guide movement of the surgical instrument, and at least one motor operatively connected to control movement of the robot arm relative to the robot base. The robot controller can control movement of the at least one motor based on the steering information to guide repositioning of the surgical instrument to become aligned with the target pose.

[0078] During surgery (i.e., the intraoperative stage) the surgical planning system **310** can be configured to provide the surgical plan to a display device to assist a user (e.g., surgeon) during surgery. In some embodiments, a surgical system includes the surgical planning system **310** as a subsystem for computer assisted navigation during surgery, a camera tracking subsystem **200** (FIGS. **6-8**), and a navigation controller **902** (FIG. **9**). As explained above, the surgical planning system **310** is configured to: obtain postoperative feedback data provided by distributed networked computers regarding surgical outcomes for a plurality of patients; train a machine learning model based on the postoperative feedback data; and obtain preoperative data from one of the distributed network computers characterizing a defined-patient, generate a spinal surgery plan for the defined-patient based on processing the preoperative data through the machine learning model.

[0079] The camera tracking subsystem **200** (FIGS. **6-8**) is configured to determine the pose of the spine of the defined-patient relative to a pose of a surgical instrument manipulated by an operator and/or a surgical robot. The navigation controller **902** (FIG. **9**) is operative to obtain the spinal surgery plan from the spinal surgery navigation subsystem **310**, determine a target pose of the surgical instrument based on the spinal surgery plan indicating where a surgical procedure is to be performed on the spine of the defined-patient and based on the pose of the spine of the defined-patient, and generate steering information based on comparison of the target pose of the surgical instrument and the pose of the surgical instrument.

[0080] In some embodiments, the surgical system includes an XR headset **920** with at least one see-through display device **928** (FIG. **9**). An XR headset controller **904** may partially reside in the computer platform **900** or in the XR headset **140**, and is configured to generate a graphical representation of the steering information that is provided to the at least one see-through display device of the XR headset **920** to provide navigated guidance to the wearer according to the spinal surgery plan. For example, the navigation controller may be operative to generate a graphical representation of the steering information that is provided to XR headset controller **904** for display

through the see-through display device **928** of the XR headset **140** to guide operator movement of the surgical instrument to become aligned with a target pose according to the spinal surgery plan.

[0081] To generate the spinal surgery plan and train the machine learning model **316**, data is needed from multiple sources to establish a baseline machine learning model that is then trained over time to provide improved patent specific outcomes from the generated spinal surgery plans.

[0082] FIG. **5** illustrates an operational flowchart for generating a spinal surgery plan based on processing preoperative patient data through a spine model **504**, and for using intraoperative feedback data and/or postoperative feedback data to adapt or machine-train (via machine learning operations) the spine model **504**.

[0083] Referring to FIG. **5**, responsive to initiation of a patient case, preoperative data is provided as initial patient case inputs **500**. The preoperative initial patient case input parameters **500** may be obtained from EHR patient data and/or patient images.

[0084] The electronic health record (EHR) patient data may include, without limitation, any one or more of: [0085] 1) date of birth, which may be used to select parameters for the spine model, e.g., adult or pediatric; [0086] 2) height; [0087] 3) weight/BMI; [0088] 4) gender; [0089] 5) ethnicity; [0090] 6) race; [0091] 7) bone Density, e.g., obtained from test results of Dual-Energy X-ray Absorptiometry (DEXA) scan (t-score and z-score), and/or CT scan (Hounsfield Scale); [0092] 8) menarchal status; [0093] 9) skeletal of maturity, e.g., Sander's score; [0094] 10) complete Blood Count (CBC); [0095] 11) blood Morphogenic Proteins (BMP); [0096] 12) coagulation Factors; [0097] 13) EKGs; [0098] 14) medication history, e.g., teriparatide status or other medications influencing bone density; [0099] 15) general medical history, e.g., nicotine status, substance abuse, medical conditions, known allergies, previous failed spinal surgeries, diabetes, rheumatoid arthritis, any degenerative diseases; [0100] 16) psychological evaluation section; [0101] 17) demographic characteristics; [0102] 18) activity characteristics-physical therapy status, activity level descriptor; [0103] 19) doctor's notes; [0104] 20) past spinal surgical procedures, e.g., fusions, spinal cord stimulator, non-surgical interventions, etc.; [0105] 21) current diagnoses, e.g., pathologies/location; radiculopathy, myelopathy; and [0106] 22) patient imaging scans.

[0107] Historical data can be provided to the spine model **504** for adaptation/training of the model **504** and for use in generating machine learning-based outputs that may be used to perform the image processing **502** and/or to determine the generated information **506** and generate the candidate spine surgery plans **508**. The historical data may include, without limitation, physician Key Opinion Leader (KOL) data input and/or data from literature studies such as any one or more of: [0108] 1) spinal anatomical trends, e.g., size, shape, patterns; [0109] 2) spinal alignment parameters, e.g., accepted normative ranges; [0110] 3) spinal alignment measurement methodologies; [0111] 4) spinal stiffness matrix; [0112] 5) initial trained machine learning algorithms from preop and/or postop patient images with known outcomes; [0113] 6) surgical intervention expertise; and [0114] 7) diagnosis criteria(s).

[0115] More specifically in the context of spinal surgery, the historical data may include any one or more of: spinal alignment target values; spinal anatomical trends; surgeon approach techniques; spine stiffness data; diagnosis criteria; and known correlations for best outcomes from surgical techniques.

[0116] The patient images may be obtained from imaging devices **910** (FIG. **9**), such as a computed tomography C-arm image device and/or computed tomography O-arm imaging device, and/or may be obtained from image database(s). The patient images may be retrieved from the central database **320** (FIG. **3**) using a patient identifier.

[0117] Image processing **502** of the patient images may be performed using the spine model **504** which can be configured to generate synthetic CT image modality images of the patient's spine from MRI modality images of the patient's spine. Other image processing **502** operations can include generating synthetic CT image modality images from a plurality of fluoroscopy shots, e.g., AP and lateral fluoroscopy images.

[0118] Alternatively or additionally, the image processing may be performed using the spine model **504** which can be configured to identify anatomical key points and datums, determine segmentation, colorization, and/or identify patient spinal anatomy, e.g., bone and soft tissue structures. Sizes of the images anatomical structures can be determined based on segment locations and overall structure size. Spine stiffness and bone density may be estimated based on the image processing and the other initial case inputs. Stenosis of the spine, central and/or lateral recess, can be characterized based on processing initial case inputs **500** through the spine model **504**. Foraminal height(s), disc height(s) (e.g., anterior or posterior, medial or lateral), CSF fluid around spinal cord and nerve roots, current global alignment parameters, can be characterized based on processing initial case inputs **500** through the spine model **504** and using measurement standards.

[0119] Generated information **506** from the initial case inputs **500**, image processing **502**, and measurement standards, and historical data, along with output of the spine model **504**, can include, but is not limited to, any one or more of the following: [0120] 1) medical diagnoses of the patient, such as inputs from surgeon and/or output from the spine model **504**; [0121] 2) one or more candidate spine surgery plans; [0122] 3) predication of likelihood of complications from surgery performed according to the one or more candidate spine surgery plans, which may be based on inputs from surgeon and/or output from the spine model **504**; [0123] 4) predicted ideal global alignment parameters and level of intervention needed; [0124] 5) approach options with predicted outcomes displayed as function of: [0125] i. direct versus indirect, e.g., when is indirect decompression a sufficient intervention; [0126] ii. indirect decompression options and/or scenarios; [0127] iii. implant auto-plans, e.g., interbody size, location, lordosis or expansion parameters, fixation implant size and/or location, rod size and/or diameter and/or material, collision avoidance, instrument depth control set points; [0128] iv. deformity solution(s); [0129] v. auto-plan of rod curvature to align with posterior instrumentation and ability to translate that plan to an automatic rod bender instrument; [0130] vi. foraminal and/or spinal canal height restoration prediction; and [0131] vii. alignment correction.

[0132] The surgeon reviews **510** the one or more candidate spine surgery plans and may approve (select) one of the candidate spine surgery plans or adjust one of the candidate spine surgery plans for approval. The approved candidate spine surgery plan is provided as preoperative feedback to train the spine model **504**.

[0133] The approved candidate spine surgery plan can be provided to the intraoperative guidance component **314** (FIG. **3**) where it can be used to generate navigation information to guide an surgeon or other personnel through a spinal surgery procedure according to the approved candidate spine surgery plan. Alternatively or additionally, the intraoperative guidance component **314** may provide the approved candidate spine surgery plan as steering information to the robot controller to control movement of the robot arm according to the approved candidate spine surgery plan.

[0134] Intraoperative data is collected **512** and is provided as intraoperative feedback for training the spine model **504**. The Intraoperative data can include, but is not limited to, any one or more of the following: [0135] 1) finalized implant plans, e.g., spine level, type (VBR, disc replacement, interbody spacer), size, expansion parameters, location data in reference to anatomical key points and implant position; [0136] 2) finalized access approach, e.g., anterior cervical discectomy and fusion (ACDF), Posterior Cervical, lateral lumbar interbody fusion (LLIF), anterior lumbar interbody fusion (ALIF), posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF), etc.; [0137] 3) Port sizes used, such as biportal or uniportal sizes; [0138] 4) intraoperative vertebral body and instrumentation navigation and location history tracking, which may include any one or more of: [0139] i. comparison of tracked vertebral body alignment measures; [0140] ii. degree of soft tissue disruption, e.g., based on approach, access style, level of decompression; [0141] iii. degree of direct decompression or resection; [0142] iv. port size used, which may include total working region versus actual bone removed within a working region; [0143] v. implant cannula placement; [0144] vi. degree of discectomy tissue removed; [0145] vii.

force measurements, e.g., from corrective loads, implant loads; and [0146] viii. stiffness sensors; [0147] 5) smart driver information feedback on torque and expansion; [0148] 6) smart implant information feedback on load and/or force distributions across implant, position; [0149] 7) neuromonitoring data; [0150] 8) ultrasonics data; [0151] 9) biologics used; [0152] 10) robot surgery system operation data logs; [0153] 11) surgical time, e.g., access, decompressions, discectomy, interbody placement, fixation placement, overall, etc; [0154] 12) re-registration scans; and [0155] 13) updates to measured parameters and/or plan based on new registration.

[0156] After the patient surgical procedure has been completed (end patient case), postoperative data is collected **514** and is provided as postoperative feedback for training the spine model **504**. The postoperative data can include, but is not limited to, any one or more of the following: [0157] 1) Patient Reported Outcomes (PROs); [0158] 2) postoperative patient imaging scans; [0159] 3) deviation of spinal surgery plan versus actual placement of implants, which may be determined through preoperative patient imaging scans with implant plans compared to postoperative patient imaging scans; [0160] 4) expected lordosis and/or correction compared to actual, e.g., which can be used to establish expected accuracies and outcomes and which indicate height restoration such as disc height, foraminal height (left vs. right), etc.; [0161] 5) implant failures; [0162] 6) bone failures; [0163] 7) fusion rates; [0164] 8) ASD reporting (levels affected in relation to surgical intervention, evidence of facet violation (if any)); [0165] 9) Patient Reported Outcome Measures (PROMs); and [0166] 10) short-term and long-term patient medical data measurements, and observed changes over time in the data measurements.

[0167] Through machine learning, anatomical standards, pre/intra/post-operative data collection, and known patient outcomes), the spine model **504** can be trained and eventually be predictive enough to determine or suggest possible diagnoses, determine ideal access approach(es), degree of decompression needed (indirect and/or direct), required interbody size/placement, custom interbody expansion set points (height and lordosis), and fixation type/size/placement that would be required for the most ideal spinal correction and patient outcomes. The need for this type of capability ranges from complex spinal deformity cases to single level degenerative spinal cases, like in the ILIF procedure, and could be beneficial for every type of spinal correction surgery including vertebral body replacements, and disc replacements.

[0168] Improvement of preoperative spinal surgery plans can be provided by analysis of intraoperative and postoperative data. Use of the preoperative feedback, intraoperative feedback, and postoperative feedback to train the spine model **504** can enable more accurate prediction of patient specific outcomes through a candidate spine surgery plan and the generation of the spine surgery plan can be optimized to provide more optimal patient specific outcomes. The spine surgery plan generated using the trained spine model **504** can use more optimally selected procedure types, implant types, access types, levels (amount) of decompression needed (indirect versus direct, and amount (degrees) of either), etc. The operations can be performed using x-ray imaging, endoscopic camera imaging, and/or ultrasonic imaging. The spinal surgery plan(s) can be generated based on learned surgeon preference(s) and/or learned standard best practices.

[0169] Various embodiments of the present disclosure may use postoperatively obtained data for correlation with a surgical plan and execution in order to: [0170] Provide guidance information that enables a user to understand performance metrics that are predicted to be obtained through the selection of available surgical plan variables; and [0171] Provide machine learning, such may include artificial intelligence (AI), assistance to a surgeon when performing patient-specific planning: [0172] Defining target deformity correction(s) and/or joint line(s) through the planned surgical procedure; and/or [0173] Defining selection of a best implant for use with the patient.

[0174] FIG. **6** is an overhead view of a surgical system arranged during a surgical procedure in a surgical room. The system includes a camera tracking system **200** for computer assisted navigation during surgery and may further include a surgical robot **100** for robotic assistance according to some embodiments. FIG. **7** illustrates the camera tracking system **200** and the surgical robot **100**

positioned relative to a patient according to some embodiments. FIG. **8** further illustrates the camera tracking system **200** and the surgical robot **100** configured according to some embodiments. FIG. **9** illustrates a block diagram of a surgical system that includes headsets **140** (e.g., extended reality (XR) headsets), a computer platform **900**, imaging devices **910**, and the surgical robot **100** which are configured to operate according to some embodiments.

[0175] The XR headsets **140** may be configured to augment a real-world scene with computer generated XR images while worn by personnel in the operating room. The XR headsets **140** may be configured to provide an augmented reality (AR) viewing environment by displaying the computer generated XR images on a see-through display screen that allows light from the real-world scene to pass therethrough for combined viewing by the user. Alternatively, the XR headsets **140** may be configured to provide a virtual reality (VR) viewing environment by preventing or substantially preventing light from the real-world scene from being directly viewed by the user while the user is viewing the computer-generated AR images on a display screen. The XR headsets **140** can be configured to provide both AR and VR viewing environments. Thus, the term XR headset can be referred to as an AR headset or a VR headset.

[0176] Referring to FIGS. **6** through **9**, the surgical robot **100** may include one or more robot arms **104**, a display **110**, an end-effector **112** (e.g., a guide tube **114**), and an end effector reference element which can include one or more tracking fiducials. A patient reference element **116** (DRB) has a plurality of tracking fiducials and is secured directly to the patient **210** (e.g., to a bone of the patient). A reference element **144** is attached or formed on an instrument, surgical tool, surgical implant device, etc.

[0177] The camera tracking system **200** includes tracking cameras **204** which may be spaced apart stereo cameras configured with partially overlapping field-of-views. The camera tracking system **200** can have any suitable configuration of arm(s) **202** to move, orient, and support the tracking cameras **204** in a desired location, and may contain at least one processor operable to track location of an individual fiducial and pose of an array of fiducials of a reference element.

[0178] As used herein, the term "pose" refers to the location (e.g., along 3 orthogonal axes) and/or the rotation angle (e.g., about the 3 orthogonal axes) of fiducials (e.g., DRB) relative to another fiducial (e.g., surveillance fiducial) and/or to a defined coordinate system (e.g., camera coordinate system, navigation coordinate system, etc.). A pose may therefore be defined based on only the multidimensional location of the fiducials relative to another fiducial and/or relative to the defined coordinate system, based on only the multidimensional rotational angles of the fiducials relative to the other fiducial and/or to the defined coordinate system, or based on a combination of the multidimensional location and the multidimensional rotational angles. The term "pose" therefore is used to refer to location, rotational angle, or combination thereof.

[0179] The tracking cameras **204** may include, e.g., infrared cameras (e.g., bifocal or stereophotogrammetric cameras), operable to identify, for example, active and passive tracking fiducials for single fiducials (e.g., surveillance fiducial) and reference elements which can be formed on or attached to the patient **210** (e.g., patient reference element, DRB, etc.), end effector **112** (e.g., end effector reference element), XR headset(s) **140** worn by a surgeon **120** and/or a surgical assistant **126**, etc. in a given measurement volume of a camera coordinate system while viewable from the perspective of the tracking cameras **204**. The tracking cameras **204** may scan the given measurement volume and detect light that is emitted or reflected from the fiducials in order to identify and determine locations of individual fiducials and poses of the reference elements in three-dimensions. For example, active reference elements may include infrared-emitting fiducials that are activated by an electrical signal (e.g., infrared light emitting diodes (LEDs)), and passive reference elements may include retro-reflective fiducials that reflect infrared light (e.g., they reflect incoming IR radiation into the direction of the incoming light), for example, emitted by illuminators on the tracking cameras **204** or other suitable device.

[0180] The XR headsets **140** may each include tracking cameras (e.g., spaced apart stereo cameras)

that can track location of a surveillance fiducial and poses of reference elements within the XR camera headset field-of-views (FOVs) **141** and **142**, respectively. Accordingly, as illustrated in FIG. **6**, the location of the surveillance fiducial and the poses of reference elements on various objects can be tracked while in the FOVs **141** and **142** of the XR headsets **140** and/or a FOV **600** of the tracking cameras **204**.

[0181] FIGS. **6** and **7** illustrate a potential configuration for the placement of the camera tracking system **200** and the surgical robot **100** in an operating room environment. Computer assisted navigated surgery can be provided by the camera tracking system controlling the XR headsets **140** and/or other displays **34**, **36**, and **110** to display surgical procedure navigation information. The surgical robot **100** is optional during computer assisted navigated surgery.

[0182] The camera tracking system **200** may operate using tracking information and other information provided by multiple XR headsets **140** such as inertial tracking information and optical tracking information (frames of tracking data). The XR headsets **140** operate to display visual information and may play-out audio information to the wearer. This information can be from local sources (e.g., the surgical robot **100** and/or other medical), imaging devices **910** (FIG. **11**), and remote sources (e.g., patient medical image database), and/or other electronic equipment. The camera tracking system **200** may track fiducials in 6 degrees-of-freedom (6 DOF) relative to three axes of a 3D coordinate system and rotational angles about each axis. The XR headsets **140** may also operate to track hand poses and gestures to enable gesture-based interactions with "virtual" buttons and interfaces displayed through the XR headsets **140** and can also interpret hand or finger pointing or gesturing as various defined commands. Additionally, the XR headsets **140** may have a 1-10× magnification digital color camera sensor called a digital loupe. In some embodiments, one or more of the XR headsets **140** are minimalistic XR headsets that display local or remote information but include fewer sensors and are therefore more lightweight.

[0183] An "outside-in" machine vision navigation bar supports the tracking cameras **204** and may include a color camera. The machine vision navigation bar generally has a more stable view of the environment because it does not move as often or as quickly as the XR headsets **140** while positioned on wearers' heads. The patient reference element **116** (DRB) is generally rigidly attached to the patient with stable pitch and roll relative to gravity. This local rigid patient reference **116** can serve as a common reference for reference frames relative to other tracked elements, such as a reference element on the end effector **112**, instrument reference element **144**, and reference elements on the XR headsets **140**.

[0184] When present, the surgical robot (also "robot") may be positioned near or next to patient **210**. The robot **100** can be positioned at any suitable location near the patient **210** depending on the area of the patient **210** undergoing the surgical procedure. The camera tracking system **200** may be separate from the robot system **100** and positioned at the foot of patient **210**. This location allows the tracking camera **200** to have a direct visual line of sight to the surgical area **208**. In the configuration shown, the surgeon **120** may be positioned across from the robot **100**, but is still able to manipulate the end-effector **112** and the display **110**. A surgical assistant **126** may be positioned across from the surgeon **120** again with access to both the end-effector **112** and the display **110**. If desired, the locations of the surgeon **120** and the assistant **126** may be reversed. An anesthesiologist **122**, nurse or scrub tech can operate equipment which may be connected to display information from the camera tracking system **200** on a display **34**.

[0185] With respect to the other components of the robot **100**, the display **110** can be attached to the surgical robot **100** or in a remote location. End-effector **112** may be coupled to the robot arm **104** and controlled by at least one motor. In some embodiments, end-effector **112** includes a guide tube **114**, which is configured to receive and orient a surgical instrument, tool, or implant used to perform a surgical procedure on the patient **210**. In some other embodiments, the end-effector **112** includes a passive structure guiding a saw blade (e.g., sagittal saw) along a defined cutting plate.

[0186] As used herein, the term "end-effector" is used interchangeably with the terms "end-

effectuator" and "effectuator element." The term "instrument" is used in a non-limiting manner and can be used interchangeably with "tool" and "implant" to generally refer to any type of device that can be used during a surgical procedure in accordance with embodiments disclosed herein. The more general term device can also refer to structure of the end-effector, etc. Example instruments, tools, and implants include, without limitation, drills, screwdrivers, saws, dilators, retractors, probes, implant inserters, and implant devices such as a screws, spacers, interbody fusion devices, plates, rods, etc. Although generally shown with a guide tube **114**, it will be appreciated that the end-effector **112** may be replaced with any suitable instrumentation suitable for use in surgery. In some embodiments, end-effector **112** can comprise any known structure for effecting the movement of the surgical instrument in a desired manner.

[0187] The surgical robot **100** is operable to control the translation and orientation of the end-effector **112**. The robot **100** may move the end-effector **112** under computer control along x-, y-, and z-axes, for example. The end-effector **112** can be configured for selective rotation about one or more of the x-, y-, and z-axis, and a Z Frame axis, such that one or more of the Euler Angles (e.g., roll, pitch, and/or yaw) associated with end-effector **112** can be selectively computer controlled. In some embodiments, selective control of the translation and orientation of end-effector **112** can permit performance of medical procedures with significantly improved accuracy compared to conventional robots that utilize, for example, a 6 DOF robot arm comprising only rotational axes. For example, the surgical robot **100** may be used to operate on patient **210**, and robot arm **104** can be positioned above the body of patient **210**, with end-effector **112** selectively angled relative to the z-axis toward the body of patient **210**.

[0188] In some example embodiments, the XR headsets **140** can be controlled to dynamically display an updated graphical indication of the pose of the surgical instrument so that the user can be aware of the pose of the surgical instrument at all times during the procedure.

[0189] In some further embodiments, surgical robot **100** can be operable to correct the path of a surgical instrument guided by the robot arm **104** if the surgical instrument strays from the selected, preplanned trajectory. The surgical robot **100** can be operable to permit stoppage, modification, and/or manual control of the movement of end-effector **112** and/or the surgical instrument. Thus, in use, a surgeon or other user can use the surgical robot **100** as part of computer assisted navigated surgery, and has the option to stop, modify, or manually control the autonomous or semi-autonomous movement of the end-effector **112** and/or the surgical instrument.

[0190] Fiducials of reference elements can be formed on or connected to robot arms **102** and/or **104**, the end-effector **112** (e.g., end-effector element **114** in FIG. **9**), and/or a surgical instrument (e.g., instrument element **144**) to enable tracking of poses in a defined coordinate system, e.g., such as in 6 DOF along 3 orthogonal axes and rotation about the axes. The reference elements enable each of the marked objects (e.g., the end-effector **112**, the patient **210**, and the surgical instruments) to be tracked by the tracking camera **200**, and the tracked poses can be used to provide navigated guidance during a surgical procedure and/or used to control movement of the surgical robot **100** for guiding the end-effector **112** and/or an instrument manipulated by the end-effector **112**.

[0191] Referring to FIG. **10** the surgical robot **100** may include a display **110**, upper arm **102**, lower arm **104**, end-effector **112**, vertical column **812**, casters **814**, a handles **818**, and ring **824** which uses lights to indicate statuses and other information. Cabinet **106** may house electrical components of surgical robot **100** including, but not limited to, a battery, a power distribution module, a platform interface board module, and a computer. The camera tracking system **200** may include a display **36**, tracking cameras **204**, arm(s) **202**, a computer housed in cabinet **800**, and other components.

[0192] In computer assisted navigated surgeries, perpendicular 2D scan slices, such as axial, sagittal, and/or coronal views, of patient anatomical structure are displayed to enable user visualization of the patient's anatomy alongside the relative poses of surgical instruments. An XR headset or other display can be controlled to display one or more 2D scan slices of patient anatomy

along with a 3D graphical model of anatomy. The 3D graphical model may be generated from a 3D scan of the patient, e.g., by a CT scan device, and/or may be generated based on a baseline model of anatomy which isn't necessarily formed from a scan of the patient.

Example Surgical System

[0193] FIG. **9** illustrates a block diagram of a surgical system that includes an XR headset **140**, a computer platform **900**, imaging devices **910**, and a surgical robot **100** which are configured to operate according to some embodiments. The computer platform **900** may include the surgical planning system **310** containing the computer platform configured to operate according to one or more of the embodiments disclosed herein.

[0194] The imaging devices **910** may include a C-arm imaging device, an O-arm imaging device, and/or a patient image database. The XR headset **140** provides an improved human interface for performing navigated surgical procedures. The XR headset **140** can be configured to provide functionalities, e.g., via the computer platform **900**, that include without limitation any one or more of: identification of hand gesture-based commands, display XR graphical objects on a display device **928** of the XR headset **140** and/or another display device. The display device **928** may include a video projector, flat panel display, etc. The user may view the XR graphical objects as an overlay anchored to particular real-world objects viewed through a see-through display screen. The XR headset **140** may additionally or alternatively be configured to display on the display device **928** video streams from cameras mounted to one or more XR headsets **140** and other cameras.

[0195] Electrical components of the XR headset **140** can include a plurality of cameras **920**, a microphone **922**, a gesture sensor **924**, a pose sensor **926** (e.g., inertial measurement unit (IMU)), the display device **928**, and a wireless/wired communication interface **930**. The cameras **920** of the XR headset **140** may be visible light capturing cameras, near infrared capturing cameras, or a combination of both.

[0196] The cameras **920** may be configured to operate as the gesture sensor **924** by tracking for identification user hand gestures performed within the field-of-view of the camera(s) **920**. Alternatively, the gesture sensor **924** may be a proximity sensor and/or a touch sensor that senses hand gestures performed proximately to the gesture sensor **924** and/or senses physical contact, e.g., tapping on the sensor **924** or its enclosure. The pose sensor **926**, e.g., IMU, may include a multi-axis accelerometer, a tilt sensor, and/or another sensor that can sense rotation and/or acceleration of the XR headset **140** along one or more defined coordinate axes. Some or all of these electrical components may be contained in a head-worn component enclosure or may be contained in another enclosure configured to be worn elsewhere, such as on the hip or shoulder.

[0197] As explained above, a surgical system includes the camera tracking system **200** which may be connected to a computer platform **900** for operational processing and which may provide other operational functionality including a navigation controller **902** and/or of an XR headset controller **904**. The surgical system may include the surgical robot **100**. The navigation controller **902** can be configured to provide visual navigation guidance to an operator for moving and positioning a surgical tool relative to patient anatomical structure based on a surgical plan, e.g., from a surgical planning function, defining where a surgical procedure is to be performed using the surgical tool on the anatomical structure and based on a pose of the anatomical structure determined by the camera tracking system **200**. The navigation controller **902** may be further configured to generate navigation information based on a target pose for a surgical tool, a pose of the anatomical structure, and a pose of the surgical tool and/or an end effector of the surgical robot **100**. The navigation information may be displayed through the display device **928** of the XR headset **140** and/or another display device to indicate where the surgical tool and/or the end effector of the surgical robot **100** should be moved to perform a surgical procedure according to a defined surgical plan.

[0198] The electrical components of the XR headset **140** can be operatively connected to the electrical components of the computer platform **900** through the wired/wireless interface **930**. The electrical components of the XR headset **140** may be operatively connected, e.g., through the

computer platform **900** or directly connected, to various imaging devices **910**, e.g., the C-arm imaging device, the I/O-arm imaging device, the patient image database, and/or to other medical equipment through the wired/wireless interface **930**.

[0199] The surgical system may include a XR headset controller **904** that may at least partially reside in the XR headset **140**, the computer platform **900**, and/or in another system component connected via wired cables and/or wireless communication links. Various functionality is provided by software executed by the XR headset controller **904**. The XR headset controller **904** is configured to receive information from the camera tracking system **200** and the navigation controller **902**, and to generate an XR image based on the information for display on the display device **928**.

[0200] The XR headset controller **904** can be configured to operationally process frames of tracking data from tracking cameras from the cameras **920** (tracking cameras), signals from the microphone **1620**, and/or information from the pose sensor **926** and the gesture sensor **924**, to generate information for display as XR images on the display device **928** and/or for display on other display devices for user viewing. Thus, the XR headset controller **904** illustrated as a circuit block within the XR headset **140** is to be understood as being operationally connected to other illustrated components of the XR headset **140** but not necessarily residing within a common housing or being otherwise transportable by the user. For example, the XR headset controller **904** may reside within the computer platform **900** which, in turn, may reside within the cabinet **800** of the camera tracking system **200**, the cabinet **106** of the surgical robot **100**, etc.

Further Definitions and Embodiments

[0201] In the above-description of various embodiments of present inventive concepts, it is to be understood that the terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of present inventive concepts. Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which present inventive concepts belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense expressly so defined herein.

[0202] When an element is referred to as being "connected", "coupled", "responsive", or variants thereof to another element, it can be directly connected, coupled, or responsive to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected", "directly coupled", "directly responsive", or variants thereof to another element, there are no intervening elements present. Like numbers refer to like elements throughout. Furthermore, "coupled", "connected", "responsive", or variants thereof as used herein may include wirelessly coupled, connected, or responsive. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. Well-known functions or constructions may not be described in detail for brevity and/or clarity. The term "and/or" includes any and all combinations of one or more of the associated listed items.

[0203] It will be understood that although the terms first, second, third, etc. may be used herein to describe various elements/operations, these elements/operations should not be limited by these terms. These terms are only used to distinguish one element/operation from another element/operation. Thus, a first element/operation in some embodiments could be termed a second element/operation in other embodiments without departing from the teachings of present inventive concepts. The same reference numerals or the same reference designators denote the same or similar elements throughout the specification.

[0204] As used herein, the terms "comprise", "comprising", "comprises", "include", "including", "includes", "have", "has", "having", or variants thereof are open-ended, and include one or more

stated features, integers, elements, steps, components or functions but does not preclude the presence or addition of one or more other features, integers, elements, steps, components, functions or groups thereof. Furthermore, as used herein, the common abbreviation "e.g.", which derives from the Latin phrase "exempli gratia," may be used to introduce or specify a general example or examples of a previously mentioned item, and is not intended to be limiting of such item. The common abbreviation "i.e.", which derives from the Latin phrase "id est," may be used to specify a particular item from a more general recitation.

[0205] Example embodiments are described herein with reference to block diagrams and/or flowchart illustrations of computer-implemented methods, apparatus (systems and/or devices) and/or computer program products. It is understood that a block of the block diagrams and/or flowchart illustrations, and combinations of blocks in the block diagrams and/or flowchart illustrations, can be implemented by computer program instructions that are performed by one or more computer circuits. These computer program instructions may be provided to a processor circuit of a general purpose computer circuit, special purpose computer circuit, and/or other programmable data processing circuit to produce a machine, such that the instructions, which execute via the processor of the computer and/or other programmable data processing apparatus, transform and control transistors, values stored in memory locations, and other hardware components within such circuitry to implement the functions/acts specified in the block diagrams and/or flowchart block or blocks, and thereby create means (functionality) and/or structure for implementing the functions/acts specified in the block diagrams and/or flowchart block(s).

[0206] These computer program instructions may also be stored in a tangible computer-readable medium that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer-readable medium produce an article of manufacture including instructions which implement the functions/acts specified in the block diagrams and/or flowchart block or blocks. Accordingly, embodiments of present inventive concepts may be embodied in hardware and/or in software (including firmware, resident software, micro-code, etc.) that runs on a processor such as a digital signal processor, which may collectively be referred to as "circuitry," "a module" or variants thereof.

[0207] It should also be noted that in some alternate implementations, the functions/acts noted in the blocks may occur out of the order noted in the flowcharts. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved. Moreover, the functionality of a given block of the flowcharts and/or block diagrams may be separated into multiple blocks and/or the functionality of two or more blocks of the flowcharts and/or block diagrams may be at least partially integrated. Finally, other blocks may be added/inserted between the blocks that are illustrated, and/or blocks/operations may be omitted without departing from the scope of inventive concepts. Moreover, although some of the diagrams include arrows on communication paths to show a primary direction of communication, it is to be understood that communication may occur in the opposite direction to the depicted arrows.

[0208] Many variations and modifications can be made to the embodiments without substantially departing from the principles of the present inventive concepts. All such variations and modifications are intended to be included herein within the scope of present inventive concepts. Accordingly, the above disclosed subject matter is to be considered illustrative, and not restrictive, and the appended examples of embodiments are intended to cover all such modifications, enhancements, and other embodiments, which fall within the spirit and scope of present inventive concepts. Thus, to the maximum extent allowed by law, the scope of present inventive concepts is to be determined by the broadest permissible interpretation of the present disclosure including the following examples of embodiments and their equivalents, and shall not be restricted or limited by the foregoing detailed description.

Claims

1. A surgical planning system to provide computer assisted navigation for spinal surgery, the surgical planning system comprises a computer platform operative to: obtain images of at least two different postures of a patient's spine; measure displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine; estimate stiffness of the patient's spine based on the measurements of displacement; generate a patient-specific kinematic model of the patient's spine based on the estimated stiffness; and provide a surgical plan based on the patient-specific kinematic model of the patient's spine.

2. The surgical planning system of claim 1, wherein the measurement of displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine, comprises to: measure the displacement of anatomical features of the patient's spine between images obtained by at least two different imaging modalities among a group of: computerized tomography (CT) imaging; magnetic resonance imaging (MRI); Cone Beam Computerized Tomography (CBCT) imaging; Micro Computerized Tomography (MCT) imaging; 3D ultrasound imaging, x-ray imaging, and fluoroscopy imaging.

3. The surgical planning system of claim 1, wherein the measurement of displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine, comprises to: measure the displacement of anatomical features of the patient's spine between at least two different ones of: a supine posture image of the patient's spine; a prone posture image of the patient's spine; a lateral posture image of the patient's spine, a standing posture image of the patient's spine; and a bending posture image of the patient's spine.

4. The surgical planning system of claim 3, wherein the measurement of displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine, comprises to: measure the displacement of anatomical features of the patient's spine between a first image and a second image, wherein the first image is based on a preoperative computerized tomography (CT) image or a preoperative magnetic resonance imaging (MRI) image of the patient's spine in one of a supine posture and a prone posture, wherein the second image is based on an intraoperative CT image or an intraoperative fluoroscopy image of the patient's spine in the other one of the supine posture and the prone posture.

5. The surgical planning system of claim 1, wherein the measurement of displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine, comprises to: measure the displacement of vertebral body centers and intervertebral disc centers of the patient's spine between the images of the at least two different postures of the patient's spine.

6. The surgical planning system of claim 1, wherein the computer platform is further operative to: provide computer assisted navigation data based on the surgical plan to a display device for preoperative surgery planning and/or intraoperative assisted surgery navigation on the patient's spine, and/or provide computer assisted navigation data based on the surgical plan to a surgical robot to control movement of an end-effector of the surgical robot for computer assisted navigation during surgery on the patient's spine.

7. The surgical planning system of claim 1, wherein to estimate stiffness of the patient's spine based on the measurements of displacement, the computer platform is further operative to: determine flexibility of intervertebral joints of the patient's spine based on the measurements of displacement of the intervertebral joints of the patient's spine between the images of the at least two different postures of the patient's spine; obtain baseline biomechanical stiffness parameters of corresponding intervertebral joints of a baseline spine defined by a baseline spine model; and estimate the stiffness of the intervertebral joints of the patient's spine based on correlating the determined flexibility of the intervertebral joints of the patient's spine to the baseline biomechanical stiffness

parameters of the corresponding intervertebral joints of the baseline spine defined by the baseline spine model.

8. The surgical planning system of claim 7, wherein to generate the patient-specific kinematic model of the patient's spine based on the estimated stiffness, the computer platform is further operative to: generate a 3D model of the patient's spine based on registering the anatomical features of the patient's spine imaged in at least one of the images to corresponding anatomical features of the baseline spine defined by the baseline spine model; and generate the patient-specific kinematic model of the patient's spine using the estimate of the stiffness of the intervertebral joints of the patient's spine to operationally define relationships between levels of force applied to anatomical features of the 3D model of the patient's spine to resulting displacement of the anatomical features.

9. The surgical planning system of claim 8, wherein to generate the surgical plan based on the patient-specific kinematic model of the patient's spine, the computer platform is further operative to: obtain a target displacement of at least one anatomical feature of the patient's spine; estimate using the patient-specific kinematic model a level of force to be applied to at least one location on the patient's spine to obtain the target displacement of the at least one anatomical feature of the patient's spine.

10. The surgical planning system of claim 8, wherein to generate the surgical plan based on the patient-specific kinematic model, the computer platform is further operative to: obtain a targeted displacement of anatomical features of the patient's spine through fixation of an implant to the patient's spine; and estimate using the patient-specific kinematic model a level of force that will be exerted on a surgical implant when used to fixate anatomical features of the patient's spine at the target displacement.

11. The surgical planning system of claim 10, wherein to estimate using the patient-specific kinematic model the level of force will be exerted on the surgical implant when used to fixate anatomical features of the patient's spine at the target displacement, the computer platform is further operative to: estimate a level of force exerted on a pedicle screw to secure a spine fixation implant to fixate anatomical features of the patient's spine at the target displacement.

12. The surgical planning system of claim 1, wherein to generate the patient-specific kinematic model of the patient's spine based on the estimated stiffness, comprises to: process the images of the at least two different postures of the patient's spine through a machine learning model to generate a function relating inputted levels of force to be applied to anatomical features of the patient's spine to outputted resulting displacement of the anatomical features, wherein the machine learning model is trained to relate displacement of intervertebral joints of spines between the images of the at least two different postures of the patient's spine to stiffness of the intervertebral joints of the patient's spine.

13. The surgical planning system of claim 1, further comprising wherein the computer platform is further operative to: determine a target displacement of at least one anatomical feature of the patient's spine based on the surgical plan; obtain tool tracking data indicating pose of a tool relative to the patient's spine; obtain spine tracking data indicating pose of the at least one anatomical feature of the patient's spine; process the tool tracking data, the spine tracking data, and the target displacement of the at least one anatomical feature of the patient's spine to generate intraoperative navigated guidance data; and display the intraoperative navigated guidance data to guide a user's movement of the tool.

14. The surgical planning system of claim 1, further comprising: the surgical robot including a robot base, a robot arm connected between the robot base and an end effector, and at least one motor operatively connected to control movement of the end effector via the robot arm relative to the robot base, wherein the computer platform is further operative to determine a target displacement of at least one anatomical feature of the patient's spine based on the surgical plan; obtain tool tracking data indicating pose of a tool relative to the patient's spine; obtain spine tracking data indicating pose of the at least one anatomical feature of the patient's spine; process

the tool tracking data, the spine tracking data, and the target displacement of the at least one anatomical feature of the patient's spine to generate intraoperative navigated guidance data; and control movement of the at least one motor based on the intraoperative navigated guidance data to guide movement of the tool.

15. A method by a surgical planning system to provide computer assisted navigation for spinal surgery, the method comprising: obtaining images of at least two different postures of a patient's spine; measuring displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine; estimating stiffness of the patient's spine based on the measurements of displacement; generating a patient-specific kinematic model of the patient's spine based on the estimated stiffness; and providing a surgical plan based on the patient-specific kinematic model of the patient's spine.

16. The method of claim 15, wherein estimating stiffness of the patient's spine based on the measurements of displacement, comprises: determining flexibility of intervertebral joints of the patient's spine based on the measurements of displacement of the intervertebral joints of the patient's spine between the images of the at least two different postures of the patient's spine; obtaining baseline biomechanical stiffness parameters of corresponding intervertebral joints of a baseline spine defined by a baseline spine model; and estimating the stiffness of the intervertebral joints of the patient's spine based on correlating the determined flexibility of the intervertebral joints of the patient's spine to the baseline biomechanical stiffness parameters of the corresponding intervertebral joints of the baseline spine defined by the baseline spine model.

17. The method of claim 16, wherein generating the patient-specific kinematic model of the patient's spine based on the estimated stiffness, comprises: generating a 3D model of the patient's spine based on registering the anatomical features of the patient's spine imaged in at least one of the images to corresponding anatomical features of the baseline spine defined by the baseline spine model; and generating the patient-specific kinematic model of the patient's spine using the estimate of the stiffness of the intervertebral joints of the patient's spine to operationally define relationships between levels of force applied to anatomical features of the 3D model of the patient's spine to resulting displacement of the anatomical features.

18. The method of claim 17, wherein generating the computer assisted navigation data based on the patient-specific kinematic model of the patient's spine, comprises: obtaining a target displacement of at least one anatomical feature of the patient's spine; estimating using the patient-specific kinematic model a level of force to be applied to at least one location on the patient's spine to obtain the target displacement of the at least one anatomical feature of the patient's spine.

19. The method of claim 17, wherein generating the computer assisted navigation data based on the patient-specific kinematic model of the patient's spine, comprises: obtaining a target displacement of anatomical features of the patient's spine through fixation of an implant to the patient's spine; and estimating using the patient-specific kinematic model a level of force that will be exerted on a surgical implant when used to fixate anatomical features of the patient's spine at the target displacement defined by the surgical plan.

20. A computer program product comprising: a non-transitory computer readable medium storing instructions executable by a computer platform of a surgical planning system to provide computer assisted navigation for spinal surgery, the computer platform when executing the instructions is operative to: obtain images of at least two different postures of a patient's spine; measure displacement of anatomical features of the patient's spine between the images of the at least two different postures of the patient's spine; estimate stiffness of the patient's spine based on the measurements of displacement; generate a patient-specific kinematic model of the patient's spine based on the estimated stiffness; and provide a surgical plan based on the patient-specific kinematic model of the patient's spine.