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Inventor(s)	Paul; David C. et al.

IMAGE REGISTRATIONS WITH AUTOMATIC SPINAL ALIGNMENT MEASUREMENT

Abstract

A surgical planning system can be configured to automatically determine a parameter associated with an anatomical feature. The surgical planning system can include processing circuitry and memory coupled to the processing circuitry. The memory can have instructions stored therein that are executable by the processing circuitry to cause the surgical planning system to perform operations. The operations can include receiving an image of the anatomical feature. The operations can further include detecting a landmark associated with the anatomical feature within the image. The operations can further include determining the parameter associated with the anatomical feature based on the landmark. The operations can further include outputting an indication of the parameter associated with the anatomical feature.

Inventors: **Paul; David C. (Phoenixville, PA), Wang; Shubo (Malvern, PA), Srihari; Sahana (King of Prussia, PA), Yacoub; George (Lansdale, PA), Wolverton; Sarah (Phoenixville, PA)**

Applicant: **GLOBUS MEDICAL, INC.** (AUDUBON, PA)

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates to medical devices and systems, and more particularly, image registrations with automatic spinal alignment measurement.

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.

[0004] Computer-aided surgeries have been using 3D medical imaging scans ("3D scans") of patients for planning and intraoperative navigation. High-quality 3D scans usually require large imaging equipment, such as Computerized Tomography (CT) or Magnetic Resonance Imaging (MRI) equipment, typically situated in a radiology department but not available in operating rooms. The 3D scans can be registered to 2D intraoperative images obtained with readily available x-ray equipment in the operating room, such as by C-Arms. The poses of 2D x-ray images are tracked with a navigation camera, yielding their pose in camera space. Using a 2D-3D registration transform, intraoperative surgical navigation on high-quality 3D images can be provided.

SUMMARY

[0005] According to some embodiments, a surgical planning system configured to automatically determine a parameter associated with an anatomical feature is provided. The surgical planning system includes processing circuitry and memory coupled to the processing circuitry. The memory has instructions stored therein that are executable by the processing circuitry to cause the surgical planning system to perform operations. The operations include receiving an image of the anatomical feature. The operations further include detecting a landmark associated with the anatomical feature within the image. The operations further include determining the parameter associated with the anatomical feature based on the landmark. The operations further include outputting an indication of the parameter associated with the anatomical feature.

[0006] Some other embodiments are directed to corresponding methods by a surgical planning system configured to automatically determine a parameter associated with an anatomical feature. Some other embodiments are directed to corresponding to non-transitory computer readable medium for a surgical planning system configured to automatically determine a parameter associated with an anatomical feature.

[0007] Other surgery navigation 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 surgery navigation 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

[0008] 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:

[0009] FIG. **1** is a flow chart illustrating an example of operations performed by a surgical planning system to automatically determine a parameter associated with an anatomical feature captured in an image in accordance with some embodiments;

[0010] FIG. **2** is a flow chart illustrating an example of operations performed by a surgical planning system to register two images and to automatically determine a parameter associated with an anatomical feature captured in the two images in accordance with some embodiments;

[0011] FIG. **3** illustrates a navigated spinal surgery workflow which uses a surgery navigation system configured in accordance with some embodiments;

[0012] FIG. **4** illustrates a block diagram of the surgery navigation 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;

[0013] 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;

[0014] 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;

[0015] FIG. **7** illustrates the camera tracking system and the surgical robot positioned relative to a patient according to some embodiments;

[0016] FIG. **8** further illustrates the camera tracking system and the surgical robot configured according to some embodiments;

[0017] 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;

[0018] FIG. **10** illustrates an example of an image of a spine with automatically detected landmarks in accordance with some embodiments;

[0019] FIG. **11** is a flow chart illustrating an example of operations performed by a surgical planning system to automatically detect landmarks associated with a spine in accordance with some embodiments; and

[0020] FIGS. **12-14** illustrate examples of a graphical user interface (“GUI”) for interacting with a surgical planning system that performs image registration with automatic spinal alignment measurements in accordance with some embodiments.

DETAILED DESCRIPTION

[0021] 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.
[0022] There are currently two primary methods for measuring and obtaining spinal alignment measurements: 1) manually measuring images; and 2) using commercially available measuring software tools.
[0023] Manual measurement results can be highly susceptible to human error, can be time-consuming, and can be outdated in the era of electronic health records and healthcare technology. In some examples, manual measurement can require the user to know how to calculate the spinal alignment parameters of interest.
[0024] Current spinal alignment measurement software systems can still require user input to label various anatomical structures such as endplates, level identification, and posterior elements. This level of input tends to be very manual, time consuming, and highly susceptible to human error.
[0025] Both manual and software-assisted measuring methods can require experience in understanding two-dimensional ("2D") imaging and labeling of necessary anatomical landmarks. Due to the amount of time and potential for error associated with both software and traditional manual measuring methods, surgeons only measure the bare minimum alignment parameters, if the user chooses to measure at all. The lack of measurements limits the amount of research and clinical understanding of correlation these spinal alignment measurements may have with short-term and long-term outcomes.
[0026] If the user measures the spinal alignment parameters across various imaging modalities, a centralized location for the user to review how these alignment parameters change does not currently exist. Various embodiments herein describe centralizing the data for the user and ultimately relieving the surgeon from looking for parsed data across various platforms.
[0027] In some embodiments, the reliance on expert experience and the time required to identify and label imaging in totality can be substantially reduced by automating these processes. In additional or alternative embodiments, three-dimensional ("3D") visualization of the spine in various positions is limited to 3D imaging modalities such as a computed tomography ("CT"), magnetic resonance imaging ("MRI"), or EOS. In additional or alternative embodiments, a user is able to expand 3D visualization capabilities to 2D imaging modalities without requiring additional imaging and radiation exposure.
[0028] FIG. **1** is a flow chart illustrating an example of operations performed by an imaging system/surgical planning system to automatically determine a parameter associated with an anatomical feature captured in an image.
[0029] At block **1010**, the imaging system/surgical planning system receives an image of an anatomical feature. The term image can be used herein to refer to 2D imaging (e.g., fluoroscopy imaging, x-ray imaging, and EOS imaging) or 3D imaging (e.g., CT imaging or MRI imaging). In some embodiments, the image is received directly from an imaging source (e.g., a camera or imaging device). In additional or alternative embodiments, the image is received from user input.
[0030] At block **1020**, the surgical planning system detects a landmark associated with the anatomical feature within the image. In some embodiments, detecting the landmark includes determining a modality of the image of the anatomical feature and detecting the landmark based on the modality of the image. In some examples, if the modality of the image is a 3D imaging, detecting the landmark associated with the anatomical feature within the image includes processing the image to generate a two-dimensional ("2D") version of the image. Detecting the landmark can

include detecting the landmark associated with the anatomical feature within the 2D version of image.

[0031] In additional or alternative embodiments, detecting the landmark includes determining a region of the anatomical feature captured in the image and detecting the landmark based on the region of the anatomical feature captured in the image.

[0032] In additional or alternative embodiments, the landmark includes a set of landmarks. Detecting the landmark associated with the anatomical feature includes selecting the set of landmarks to be detected from a plurality of landmarks associated with a type of the anatomical feature based on at least one of: the modality of the image; and the region of the anatomical feature captured in the image. Detecting the landmark can include detecting each landmark of the set of landmarks.

[0033] In additional or alternative embodiments, the anatomical feature includes a spine and the landmark includes a plurality of landmarks associated with the spine. In some examples, the landmarks include one or more of: a superior endplate per level; an inferior endplate per level; a center of a vertebral body; a center of femoral heads; shoulder center; and clavicle center. FIG. **10** illustrates an example of an image of a spine with some landmarks labeled (e.g., a thoracolumbar bounding box, the acromioclavicular **1024**, the clavicle cephalad **1026**, and vertebrae landmarks **1028** (which can include the vertebrae body and endplate corners). FIG. **11** (further described below), illustrates an example of operations performed to detect landmarks associated with a spine.

[0034] Returning to FIG. **1**, at block **1030**, the surgical planning system determines a parameter associated with the anatomical feature based on the landmark. In some embodiments, the parameter is determined by calculating a location of a first landmark relative to a second landmark.

[0035] In embodiments in which the anatomical feature includes a spine and the landmark includes a plurality of landmarks associated with the spine, the parameter can include a plurality of alignment parameters associated with the spine. Determining the parameter can include determining the plurality of anatomical parameters based on the plurality of landmarks.

[0036] In some examples, the parameters include one or more of: [0037] an angle of pelvic incidence ("PI"); [0038] an angle of pelvic tilt ("PT"); [0039] an angle of sacral slope ("SS"); [0040] an angle of lumbar lordosis ("LL"); [0041] an angle of Upper LL; [0042] an angle of Lower LL; [0043] an angle of Thoracic Kyphosis ("TK"); [0044] an angle of PI minus LL ("PI-LL"); [0045] an angle of T1—pelvic angle ("T1-PA"); [0046] a distance of the sagittal vertical axis ("SVA"); [0047] an angle between lumbar levels L2 and L5 ("L2-L5"); [0048] an angle between lumbar levels L3 and L5 ("L3-L5"); [0049] an angle between lumbar levels L4 and L5 ("L4-L5"); [0050] a maximum positive cobb angle between levels ("Max+Cobb"); [0051] a maximum negative cobb angle between levels ("Max−Cobb"); and [0052] a distance of the coronal vertical axis ("CVA").

[0053] At block **1040**, the surgical planning system outputs an indication of the parameter associated with the anatomical feature. In some embodiments, outputting the indication of the parameter associated with the anatomical feature includes displaying a 3D model of the anatomical feature labeled with the indication of the parameter. In additional or alternative embodiments, outputting the indication of the parameter associated with the anatomical feature includes displaying a 2D image of the anatomical feature labeled with the indication of the parameter. In additional or alternative embodiments, outputting the indication of the parameter associated with the anatomical feature includes displaying a quantitative version of the parameter. In some examples, the indication of the parameter can be displayed to a surgeon during a pre-operative stage, an intra-operative stage, or a post-operative stage.

[0054] In additional or alternative embodiments, outputting the indication of the parameter associated with the anatomical feature includes transmitting the indication of the parameter to a surgery navigation system. In some examples, the indication of the parameter can be transmitted to a robotic assisted surgery system or an XR headset for use during surgery.

[0055] In additional or alternative embodiments, outputting the indication of the parameter includes determining a classification associated with the anatomical feature based on the alignment parameter and outputting an indication of the classification.
[0056] In some embodiments, automatic 2D spinal alignment measurements can be obtained from 3D imaging modalities. Automated preoperative, intraoperative, and postoperative measurements of a spine can be obtained from 3D imaging modalities such as CT and MRI by running a received (or uploaded) image through various algorithms. Upon CT or MRI upload, the image (or images) can be processed and landmarks can be automatically detected and labeled. With all required points of interest detected and labeled, the surgical planning system can automatically measure and display spinal alignment measurements to the user in quantitative and/or qualitative formats from the 3D image. In some examples, the only user intervention required is uploading of the 3D images.
[0057] FIG. **11** illustrates an example of operations performed by a surgical planning system to automatically detect landmarks associated with a spine in an image of the spine. Digital radiographs may undergo preprocessing (block **1110**) before both an anatomy detection ML algorithm (block **1112**) and an imaging plane identification ML algorithm (block **1114**) are applied to the digital radiographs. At block **1112**, the anatomy detection ML algorithm may detect anatomical elements (e.g., a thoracic spine, lumbar spine, and/or femoral heads) in order to identify a bounding box of a thoracolumbar region of the spine within the digital radiographs.
[0058] At block **1114**, the imaging plane identification ML algorithm may be applied in order to determine whether the digital radiographs are from an anterior/posterior ("AP") perspective or lateral ("LAT") perspective of the spine. Based on this determination (and using the bounding box of the thoracolumbar region), the surgical planning system may use either the LAT landmark detection pipeline **1120** or the AP landmark detection pipeline **1130**. In both landmark detection pipelines **1120**, **1130** the surgical planning system can crop the digital radiographs to only include the thoracolumbar region.
[0059] At block **1120** the LAT landmark detection pipeline can apply a vertebrae landmark detection ML algorithm, which can automatically detect for each vertebrae (e.g., C7 through S1 vertebrae) a body center and endplate corner (e.g., patient anterior/posterior corners).
[0060] At block **1130** the AP landmark detection pipeline can apply a vertebrae landmark detection ML algorithm and a clavicle landmark detection ML algorithm. The vertebrae landmark detection ML algorithm can automatically detect for each vertebrae (e.g., C7 through S1 vertebrae) a body center and endplate corner (e.g., image left/right corners). The clavicle landmark detection ML algorithm can detect the clavicle cephalad point and the acromioclavicular joint.
[0061] At block **1140**, the surgical planning system can perform post-processing and verification based on vertebral disc height and vertebral body size (which can be determined by measuring the distance between the detected landmarks).
[0062] FIG. **12** illustrates an example of a graphical user interface ("GUI") **1050** for interacting with a surgical planning system that has performed automatic 2D spinal alignment measurements based on a 3D image. In this example, the left portion of the GUI **1050** includes a coronal image **1062** and a sagittal image **1064** including indications of a selection of spinal alignment measurements (e.g., Thoracic Kyphosis, Lumbar Lordosis, SVA, and Pelvic Tilt). In other examples, the images **1062**, **1064** may additionally or alternatively include indications of the landmarks that were detected.
[0063] The center portion of the GUI **1050** includes a 3D model **1090** of the spine. In some examples (as explained further in regards to FIG. **2**), the 3D model **1090** can be a representative of a 2D spine position from 2D images in 3D space.
[0064] The right portion of the GUI **1050** includes a quantitative listing **1072** of the spinal alignment measurements, a listing of normative values **1074** corresponding to some of the spinal alignment parameters, and an indication of spinal deformity classification **1080**. The spinal

alignment measurements can be selected (or deselected) to adjust which spinal alignment measurements are being displayed on the images **1062**, **1064**.

[0065] The normative values **1074** can be an expected and/or acceptable range based on characteristics of the patient (e.g., age). In this example the window displaying the normative values is too small to list the entire range. However, the size and position of each of the windows in the GUI **1050** can be adjusted based on user preferences.

[0066] In this example, the deformity classification includes a GAP score, a SRS-Schwab classification; and a Roussouly classification. However, the deformity classification can include any suitable classification (e.g., a Lenke classification). In some examples, the user can select which deformity classifications are calculated and/or displayed. In additional or alternative examples, the user can select specific deformity classifications to be indicated on the images **1062**, **1064**.

[0067] In additional or alternative embodiments, automatic 2D spinal alignment measurements can be obtained from 2D imaging modalities. Automated preoperative, intraoperative, and postoperative measurements of the spine can be obtained from 2D imaging modalities such as fluroro, x-ray, or EOS by running the received (or uploaded) image through various algorithms. Upon image upload, landmarks can be automatically detected and labeled. With all required points of interest detected and labeled, the surgical planning system can automatically measure and display spinal alignment measurements to the user in quantitative and/or qualitative formats from the 2D image. In some examples, the only user intervention required is uploading of the 2D images.

[0068] FIG. **13** illustrates an example of a GUI **1150** for interacting with a surgical planning system that has performed automatic 2D spinal alignment measurements based on a 2D image. In this example, the left portion of the GUI **1150** includes a coronal image **1162** and a sagittal image **1164** including indications of a selection of landmarks and indication of a selected spinal alignment measurement (e.g., pelvic incidence). In some examples the landmarks can include each vertebrae, the superior endplate per level, the inferior endplate per level, the center of the vertebral body, the center of the femoral heads, the shoulder center, and the clavicle center.

[0069] The right portion of the GUI **1150** includes a quantitative listing **1172** of the spinal alignment measurements, a listing of normative values **1174** corresponding to some of the spinal alignment parameters, and an indication of spinal deformity classification **1180**. The quantitative listing **1172** includes a similar selection of spinal alignment measurements to the quantitative listing **1072** in FIG. **12**. The spinal alignment measurements can be selected (or deselected) to adjust which spinal alignment measurements are being displayed on the images **1162**, **1164**.

[0070] The normative values **1174** can be an expected and/or acceptable range based on characteristics of the patient (e.g., age). In this example the window displaying the normative values is too small to list the entire range. However, the size and position of each of the windows in the GUI **1150** can be adjusted based on user preferences.

[0071] In this example, the deformity classification includes a GAP score, a SRS-Schwab classification; and a Roussouly classification. However, the deformity classification can include any suitable classification (e.g., a Lenke classification). In some examples, the user can select which deformity classifications are calculated and/or displayed. In additional or alternative examples, the user can select specific deformity classifications to be indicated on the images **1162**, **1164**.

[0072] FIG. **2** is a flow chart illustrating an example of operations performed by a surgical planning system to register two images and to automatically determine a parameter associated with an anatomical feature captured in the two images.

[0073] Similarly to blocks **1010** and **1020** of FIG. **1**, at blocks **1010**a and **1020**a, the surgical planning system can receive a first image of an anatomical feature and detect a landmark associated with the anatomical feature within the first image.

[0074] Similarly to blocks **1010** and **1020** of FIG. **1**, at blocks **1010**b and **1020**b, the surgical planning system can receive a second image of an anatomical feature and detect a landmark associated with the anatomical feature within the second image.
[0075] In some embodiments, a modality of the first image is different than a modality of the second image. In additional or alternative embodiments, the first image captures a different perspective of the anatomical image than the second image. In additional or alternative embodiments, the first image and the second image are captured by different imaging sources, at different times, and/or while the patient associated with the anatomical feature is in a different position.
[0076] At block **1125**, the surgical planning system registers the first image to the second image based on the landmark associated with the anatomical feature within the first image and landmark associated with the anatomical feature within the second image. In some embodiments, a plurality of landmarks are detected within each image and the images are registered together by matching landmarks within the plurality of landmarks associated with the first image to landmarks within the plurality of landmarks associated with the second image.
[0077] At block **1130**, the surgical planning system determines a parameter associated with the anatomical feature based on the landmarks in the first image and the second image. In some embodiments, the parameter is determined based on combining an estimate of the parameter based on the landmark in the first image and an estimate of the parameter based on the landmark in the second image. In additional or alternative embodiments, the parameter is determined based on a landmark in an image generated from registering the first image and the second image together.
[0078] At block **1140**, the surgical planning system outputs the indication of the parameter associated with the anatomical feature. In some embodiments, outputting the indication of the parameter associated with the anatomical feature includes displaying a 3D model of the anatomical feature labeled with the indication of the parameter. In additional or alternative embodiments, outputting the indication of the parameter associated with the anatomical feature includes displaying a 2D image of the anatomical feature labeled with the indication of the parameter. In additional or alternative embodiments, outputting the indication of the parameter associated with the anatomical feature includes displaying a quantitative version of the parameter. In some examples, the indication of the parameter can be displayed to a surgeon during a pre-operative stage, an intra-operative stage, or a post-operative stage.
[0079] In additional or alternative embodiments, outputting the indication of the parameter associated with the anatomical feature includes transmitting the indication of the parameter to a surgery navigation system. In some examples, the indication of the parameter can be transmitted to a robotic assisted surgery system or an XR headset for use during surgery.
[0080] In some examples, the first image comprises a 3D image and the second image comprises a 2D image. In this example, outputting the indication of the parameter includes displaying a 3D model representing the 2D image, the 3D model labeled with the parameter.
[0081] In additional or alternative examples, the first perspective is anteroposterior and the second perspective is lateral. In this example, outputting the indication of the parameter includes displaying a 3D model based on the first 2D image and the second 2D image, the 3D model labeled with the parameter.
[0082] An example associated with 3D images to 2D imaging position via image registration with automatic spine alignment measurements is described below. In this example, using the image upload and processing operations described in FIGS. **1-2**, 2D and 3D images can be registered together to provide the surgeon a 3D visualization of the 2D spine in varying patient loading conditions (e.g., lateral bending, flexion-extension, supine, prone, or standing). A 3D image set (e.g., CT or MRI) and a 2D image set (e.g., AP and Lateral) can be received at the surgical planning system. Upon upload, the surgical planning system can process the image accordingly and automatically detect anatomical landmarks. The 3D images and 2D images can then be registered

together using these automatically detected landmarks. The registration can produce a 3D model of the spine representing the 2D spine position in 3D space (e.g., the 3D model **1090** of FIG. **10**). Additionally, spinal alignment parameters can be automatically calculated from the detected landmarks and displayed to the user. The user can then interact with the 3D model to visualize changes in spinal alignment based on the patient positioning. This tool can allow surgeons to make more informed intervention decisions for better short-term and long-term outcomes.

[0083] An example associated with a generated 3D model from 2D images via image registration with automatic spine alignment measurements is described below. In this example, using the received image and analysis outlined in the automatic 2D spinal alignment measurements from 2D imaging modalities, 2D images can be registered together to provide visualization of the 2D spine in 3D space. Using the landmarks identified in the automatic landmark detection, as 2D AP image and 2D Lateral image can be registered together to provide a 3D model representation of the spine. Additionally, spinal alignment parameters can be automatically calculated from the detected landmarks and displayed to the user.

[0084] FIG. **14** illustrates an example of a GUI **1250** for interacting with a surgical planning system. In this example, the left portion of the GUI **1250** includes a coronal image **1262** and a sagittal image **1264** including indications of a selection of landmarks (in other examples the images **1262**, **1264** could additionally or alternatively include indications of a selected spinal alignment measurements). In some examples the landmarks can include each vertebrae, the superior endplate per level, the inferior endplate per level, the center of the vertebral body, the center of the femoral heads, the shoulder center, and the clavicle center.

[0085] The right portion of the GUI **1250** includes a quantitative listing **1272** of spinal alignment measurements, a listing of normative values **1274** corresponding to some of the spinal alignment parameters, and an indication of spinal deformity classification **1280**. The quantitative listing **1272** includes a similar selection of spinal alignment measurements to the quantitative listing **1072** in FIG. **12**.

[0086] The center portion of the GUI **1250** includes a 3D model **1290** of the spine based on registering the images **1262**, **1264** together with a template spine.

[0087] In some embodiments, the automatic spinal alignment measurement methods for 2D and 3D images described above can empower surgeons with new, easily obtained insights to support their operative goals, implant selection and positioning, and ultimately improve patient outcomes across surgical procedures. By eliminating the expense of time and manual effort required to obtain any and all spinal alignment parameters and elimination of human error, surgeon will be more likely to access and use the provided information to make operative decisions. Additionally, due to the speed and ease of obtaining these spinal alignment measurements, spinal alignment details can be provided nearly in real-time intraoperatively. By providing spinal alignment measurements intraoperatively, surgeons will be able to assess progress towards their plan, adjust their surgical approach, and minimizes the risk of over-correcting or under-correcting the patient.

[0088] In additional or alternative embodiments, the image registration methods between 2D and 3D imaging modalities further equips surgeons to make informed decisions through visualization of the spine preoperatively in various functional positions (standing, bending, flexion/extension, etc.).

[0089] Without the ability to view the 2D spinal positions in 4D space, a surgeon is forced to think in 3D which can lead to unforeseen obstacles or alignment during surgery.

[0090] In additional or alternative embodiments, a user is able to interact with the 3D model preoperatively to visualize the spine in 3D space. This can be helpful in preoperative visualization of complex deformities to better prepare the surgeon for planning and executing various interventions. Specific ally for pediatric patients, the image registration of 2D images to generate a 3D model can eliminate the need for a preoperative CT or MRI.

[0091] In additional or alternative embodiments, a surgical planning system can provide a centralized location for a user to review imaging, visualize the spine in various positions, and

display spinal alignment parameters. This centralized location ultimately relieves the surgeon from looking for and at parsed data across various platforms.
[0092] In additional or alternative embodiments, a user can interact with images/models generated by the surgical planning system to adjust a location of a detected landmark. In some examples, the surgical planning system can use the adjusted location to better train a machine learning model used to detect future landmarks associated with the same and/or different patients.
[0093] 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.
[0094] 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.
[0095] Some embodiments of the present disclosure are directed to surgery navigation 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 AI-assisted spine surgery plans for better patient outcomes.
[0096] 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.
[0097] 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.
[0098] The surgery navigation 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.
[0099] 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.

[0100] 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.

[0101] This and other operational functionality can be provided by a surgery navigation system for computer assisted navigation during spinal surgery. In accordance with some embodiments, the surgery navigation 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.

[0102] 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.

[0103] Various embodiments disclosed herein are directed to improvements in operation of a surgery navigation 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 surgery navigation 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 surgery navigation 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.

[0104] 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.

[0105] 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.

[0106] FIG. **3** illustrates a navigated spinal surgery workflow which uses a surgery navigation 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 surgery navigation system **310**. During the intraoperative stage **302**, the surgery navigation 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 surgery navigation 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 surgery navigation 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**.
[0107] The example surgery navigation 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**.
[0108] 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 surgery navigation 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 surgery navigation 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.
[0109] 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.

[0110] FIG. **4** illustrates a block diagram of the surgery navigation 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.

[0111] Referring to FIG. **4**, the surgery navigation system **310** includes the feedback training component **410**, the preoperative planning component **312**, and the intraoperative guidance component **314**. The surgery navigation 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.

[0112] The surgery navigation 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**.

[0113] 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.

[0114] The operation of the surgery navigation 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.

[0115] The operation of the surgery navigation 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.

[0116] The operation of the surgery navigation 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.

[0117] In some further embodiments, the surgery navigation 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.

[0118] In some further embodiments, the surgery navigation 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.

[0119] In some further embodiments, the surgery navigation 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.

[0120] In some further embodiments, the surgery navigation 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.

[0121] 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**.

[0122] 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.

[0123] 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.

[0124] 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.

[0125] 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.

[0126] 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.

[0127] 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.

[0128] During surgery (i.e., the intraoperative stage) the surgery navigation 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 surgery navigation 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 surgery navigation 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.

[0129] 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.

[0130] 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.
[0131] 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.
[0132] 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**.
[0133] 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.
[0134] The electronic health record (EHR) patient data may include, without limitation, any one or more of: [0135] 1) date of birth, which may be used to select parameters for the spine model, e.g., adult or pediatric; [0136] 2) height; [0137] 3) weight/BMI; [0138] 4) gender; [0139] 5) ethnicity; [0140] 6) race; [0141] 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); [0142] 8) menarchal status; [0143] 9) skeletal of maturity, e.g., Sander's score; [0144] 10) complete Blood Count (CBC); [0145] 11) blood Morphogenic Proteins (BMP); [0146] 12) coagulation Factors; [0147] 13) EKGs; [0148] 14) medication history, e.g., teriparatide status or other medications influencing bone density; [0149] 15) general medical history, e.g., nicotine status, substance abuse, medical conditions, known allergies, previous failed spinal surgeries, diabetes, rheumatoid arthritis, any degenerative diseases; [0150] 16) psychological evaluation section; [0151] 17) demographic characteristics; [0152] 18) activity characteristics—physical therapy status, activity level descriptor; [0153] 19) doctor's notes; [0154] 20) past spinal surgical procedures, e.g., fusions, spinal cord stimulator, non-surgical interventions, etc.; [0155] 21) current diagnoses, e.g., pathologies/location; radiculopathy, myelopathy; and [0156] 22) patient imaging scans.
[0157] 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: [0158] 1) spinal anatomical trends, e.g., size, shape, patterns; [0159] 2) spinal alignment parameters, e.g., accepted normative ranges; [0160] 3) spinal alignment measurement methodologies; [0161] 4) spinal stiffness matrix; [0162] 5) initial trained machine learning algorithms from preop and/or postop patient images with known outcomes; [0163] 6) surgical intervention expertise; and [0164] 7) diagnosis criteria(s).
[0165] 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.
[0166] 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.
[0167] 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.
[0168] 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**.
[0169] 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.
[0170] 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: [0171] 1) medical diagnoses of the patient, such as inputs from surgeon and/or output from the spine model **504**; [0172] 2) one or more candidate spine surgery plans; [0173] 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**; [0174] 4) predicted ideal global alignment parameters and level of intervention needed; [0175] 5) approach options with predicted outcomes displayed as function of: [0176] i.direct versus indirect, e.g., when is indirect decompression a sufficient intervention; [0177] ii.indirect decompression options and/or scenarios; [0178] 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; [0179] iv.deformity solution(s); [0180] v.auto-plan of rod curvature to align with posterior instrumentation and ability to translate that plan to an automatic rod bender instrument; [0181] vi.foraminal and/or spinal canal height restoration prediction; and [0182] vii.alignment correction.
[0183] 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**.
[0184] 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.
[0185] 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: [0186] 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; [0187] 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.; [0188] 3) Port sizes used, such as biportal or uniportal sizes; [0189] 4) intraoperative vertebral body and instrumentation navigation and location history tracking, which may include any one or more of: [0190] i. comparison of tracked vertebral body alignment measures; [0191] ii. degree of soft tissue disruption, e.g., based on approach, access style, level of decompression; [0192] iii. degree of direct decompression or resection; [0193] iv.port size used,

which may include total working region versus actual bone removed within a working region; [0194] v.implant cannula placement; [0195] vi. degree of discectomy tissue removed; [0196] vii.force measurements, e.g., from corrective loads, implant loads; and [0197] viii.stiffness sensors; [0198] 5) smart driver information feedback on torque and expansion; [0199] 6) smart implant information feedback on load and/or force distributions across implant, position; [0200] 7) neuromonitoring data; [0201] 8) ultrasonics data; [0202] 9) biologics used; [0203] 10) robot surgery system operation data logs; [0204] 11) surgical time, e.g., access, decompressions, discectomy, interbody placement, fixation placement, overall, etc; [0205] 12) re-registration scans; and [0206] 13) updates to measured parameters and/or plan based on new registration.

[0207] 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: [0208] 1) Patient Reported Outcomes (PROs); [0209] 2) postoperative patient imaging scans; [0210] 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; [0211] 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.; [0212] 5) implant failures; [0213] 6) bone failures; [0214] 7) fusion rates; [0215] 8) ASD reporting (levels affected in relation to surgical intervention, evidence of facet violation (if any)); [0216] 9) Patient Reported Outcome Measures (PROMs); and [0217] 10) short-term and long-term patient medical data measurements, and observed changes over time in the data measurements.

[0218] 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.

[0219] 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.

[0220] Various embodiments of the present disclosure may use postoperatively obtained data for correlation with a surgical plan and execution in order to: [0221] 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 [0222] Provide machine learning, such may include artificial intelligence (AI), assistance to a surgeon when performing patient-specific planning: [0223] Defining target deformity correction(s) and/or joint line(s) through the planned surgical procedure; and/or [0224] Defining selection of a best implant for use with the patient.

[0225] 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.

[0226] 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.

[0227] Referring to FIGS. **6-9**, 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.

[0228] 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.

[0229] 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.

[0230] 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.

[0231] 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**.

[0232] FIGS. **6-7** 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.

[0233] 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**x 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.

[0234] 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**.

[0235] 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**.

[0236] 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.
[0237] 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.
[0238] 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.
[0239] 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**.
[0240] 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.
[0241] 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.
[0242] 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**.
[0243] 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.
[0244] 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

[0245] 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 surgery navigation system **310** containing the computer platform configured to operate according to one or more of the embodiments disclosed herein.

[0246] 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. Electrical components of the XR headset **140** can include a plurality of cameras **920**, a

[0247] 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.

[0248] 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.

[0249] 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.

[0250] 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**.

[0251] 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**.

[0252] 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

[0253] 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.

[0254] 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.

[0255] 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.

[0256] 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.

[0257] 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).

[0258] 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.

[0259] 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.

[0260] 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 configured to automatically determine a spine alignment parameter associated with an anatomical feature, the surgical planning system comprising: processing circuitry; and memory coupled to the processing circuitry and having instructions stored therein that are executable by the processing circuitry to cause the surgical planning system to perform operations including: receiving an image of the anatomical feature from an imaging device; detecting a landmark associated with the anatomical feature within the image; determining the parameter associated with the anatomical feature based on the landmark; and outputting an indication of the parameter associated with the anatomical feature.
2. The surgical planning system of claim 1, wherein detecting the landmark includes: determining a modality of the image of the anatomical feature; and detecting the landmark based on the modality of the image.
3. The surgical planning system of claim 2, wherein detecting the landmark includes: determining a region of the anatomical feature captured in the image; and detecting the landmark based on the modality of the image and the region of the anatomical feature captured in the image.
4. The surgical planning system of claim 3, wherein the landmark includes a set of landmarks, and wherein detecting the landmark associated with the anatomical feature includes: selecting the set of landmarks to be detected from a plurality of landmarks associated with a type of the anatomical feature based on at least one of: the modality of the image; and the region of the anatomical feature captured in the image; and detecting each landmark of the set of landmarks.
5. The surgical planning system of claim 2, wherein the modality of the image includes three-dimensional (“3D”) imaging, and wherein detecting the landmark associated with the anatomical feature within the image includes: processing the image to generate a two-dimensional (“2D”) version of the image; and detecting the landmark associated with the anatomical feature within the 2D version of the image.
6. The surgical planning system of claim 2, wherein the modality of the image includes at least one of: computerized tomography (“CT”) imaging; magnetic resonance imaging (“MRI”) imaging; a fluroscopy image; an x-ray image; and an EOS image.
7. The surgical planning system of claim 1, wherein outputting the indication of the parameter associated with the anatomical feature includes at least one of: displaying a three-dimensional (“3D”) model of the anatomical feature labeled with the indication of the parameter; displaying a two-dimensional (“2D”) image of the anatomical feature labeled with the indication of the parameter; displaying a quantitative version of the parameter; and transmitting the indication of the parameter to a surgery navigation system.
8. The surgical planning system of claim 1, wherein the anatomical feature includes a spine, wherein the landmark includes a plurality of landmarks associated with the spine, wherein the parameter includes a plurality of alignment parameters associated with the spine, and wherein determining the parameter includes determining the plurality of anatomical parameters based on the plurality of landmarks.
9. The surgical planning system of claim 1, wherein outputting the indication of the parameter includes: determining a classification associated with the anatomical feature based on the alignment parameter; and outputting an indication of the classification.
10. The surgical planning system of claim 1, wherein the image includes a plurality of images, wherein a first modality of a first image of the plurality of images is different than a second modality of a second image of the plurality of images, and wherein detecting the landmark includes detecting: a first landmark associated with the anatomical feature within the first image; and a

second landmark associated with the anatomical feature within the second image, the operations further including: registering the first image to the second image based on the first landmark and the second landmark.

11. The surgical planning system of claim 10, wherein the first image includes a three-dimensional (“3D”) image, wherein the second image includes a two-dimensional (“2D”) image, and wherein outputting the indication of the parameter includes displaying a 3D model representing the 2D image, the 3D model labeled with the parameter.

12. The surgical planning system of claim 1, wherein the image includes a plurality of images, wherein a first image of the plurality of images includes a first two-dimensional (“2D”) image of the anatomical feature from a first perspective, wherein a second image of the plurality of images includes a second 2D image of the anatomical feature from a second perspective that is different than the first perspective, and wherein detecting the landmark includes detecting: a first landmark associated with the anatomical feature within the first image; and a second landmark associated with the anatomical feature within the second image, the operations further including: registering the first image to the second image based on the first landmark and the second landmark.

13. The surgical planning system of claim 8, wherein the first perspective is anteroposterior, wherein the second perspective is lateral. and wherein outputting the indication of the parameter includes displaying a 3D model based on the first 2D image and the second 2D image, the 3D model labeled with the parameter.

14. A method of operating a surgical planning system to automatically determine a spine alignment parameter associated with an anatomical feature, the method comprising: receiving an image of the anatomical feature; detecting a landmark associated with the anatomical feature within the image; determining the parameter associated with the anatomical feature based on the landmark; and outputting an indication of the parameter associated with the anatomical feature.

15. The method of claim 14, wherein determining the landmark associated with the anatomical feature includes: determining a modality of the image of the anatomical feature; and determining a region of the anatomical feature captured in the image, detecting the landmark based on the modality of the image and the region of the anatomical feature captured in the image.

16. The method of claim 14, wherein outputting the indication of the parameter associated with the anatomical feature includes at least one of: displaying a three-dimensional (“3D”) model of the anatomical feature labeled with the indication of the parameter; displaying a two-dimensional (“2D”) image of the anatomical feature labeled with the indication of the parameter; displaying a quantitative version of the parameter; and transmitting the indication of the parameter to a surgery navigation system.

17. The method of claim 14, wherein the anatomical feature includes a spine, wherein the landmark includes a plurality of landmarks, wherein the parameter includes a plurality of alignment parameters associated with the spine, and wherein determining the parameter includes determining the plurality of anatomical parameters based on the plurality of landmarks.

18. The method of claim 14, wherein the image includes a plurality of images, wherein a first modality of a first image of the plurality of images is different than a second modality of a second image of the plurality of images, and wherein detecting the landmark includes detecting: a first landmark associated with the anatomical feature within the first image; and a second landmark associated with the anatomical feature within the second image, the method further comprising: registering the first image and the second image based on the first landmark and the second landmark.

19. The method of claim 14, wherein the image includes a plurality of images, wherein a first image of the plurality of images includes a first two-dimensional (“2D”) image of the anatomical feature from a first perspective, wherein a second image of the plurality of images includes a second 2D image of the anatomical feature from a second perspective that is different than the first perspective, and wherein detecting the landmark includes detecting: a first landmark associated with the anatomical feature within the first image; and a second landmark associated with the anatomical feature within the second image, the method further comprising: registering the first image and the second image based on the first landmark and the second landmark.

20. A non-transitory computer readable medium storing instructions executable by processing circuitry of a surgical planning system to cause the surgical planning system to perform operations comprising: receiving an image of an anatomical feature from an imaging device; detecting a landmark associated with the anatomical feature within the image; determining a spine alignment parameter associated with the anatomical feature based on the landmark; and outputting an indication of the parameter associated with the anatomical feature.