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“SURGICAL GPS” PROOF OF CONCEPT FOR SCOLIOSIS SURGERY

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ABSTRACT

Scoliotic deformities may be addressed with either anterior or posterior approaches for scoliosis correction procedures. While typically quite invasive, the impact of these operations may be reduced through the use of computer-assisted surgery. A combination of physician-designated anatomical landmarks and surgical ontologies allows for real-time intraoperative guidance during computer-assisted surgical interventions. Predetermined landmarks are labeled on an identical patient model, which seeks to encompass vertebrae, intervertebral disks, ligaments, and other soft tissues. The inclusion of this anatomy permits the consideration of hypothetical forces that are previously not well characterized in a patient-specific manner. Updated ontologies then suggest procedural directions throughout the surgical corridor, observing the positioning of both the physician and the anatomical landmarks of interest at the present moment. Merging patient-specific models, physician-designated landmarks, and ontologies to produce real-time recommendations magnifies the successful outcome of scoliosis correction through enhanced pre-surgical planning, reduced invasiveness, and shorted recovery time.

Keywords: Scoliosis Surgery Planning, Surgical Process, Deformable Surface, Robot Assisted Surgery, Surgical Ontologies

1 INTRODUCTION

1.1 Scoliosis

Scoliosis is a medical condition described by a spinal curvature of more than 10 degrees to the right or left in the coronal plane along with a three-dimension spinal axis deviation. When viewed from the rear, the spine can resemble an "S" or a "C" rather than a straight line. Scoliosis causes include neuromuscular problems, genetic conditions, and limb length inequality and may be classified as either congenital, idiopathic, or syndromic. Deformities may also exist in the sagittal plane, and assessing the scoliosis curvature can be done through x-rays to determine the extent of kyphosis and lordosis, the convex and concave curvatures, respectively, in the sagittal plane view of the spine. Instrumented scoliosis surgery was first performed in the 1960s, and since device and technique modifications have shown some improved surgical results (Harrington 1962). Current outcomes for the surgical management of adolescent idiopathic scoliosis (AIS) seek to prevent progression and maintain coronal and sagittal alignment, produce level shoulders, correct deformity, and save motion segments (Trobisch et al., 2013). AIS classification is useful for surgical planning and comparing postoperative results; however, choosing optimal fusion levels still remains challenging (Lenke et al., 2001). One solution for an efficient, risk-free means of scoliosis treatment is computational modeling and simulation, which may provide a methodology to determine the optimum procedure among competing therapeutic approaches. The completion of such a project will allow for the prediction of various amplitudes of the forces needed to correct the scoliotic spine. Simultaneously, additional work will provide the orthopedic surgery community with a predictive planning tool that allows physicians to explore "what-if" scenarios and will lead to a greater consensus on the treatment of scoliotic deformities.

1.2 Scoliosis Surgery

In most scoliotic cases, the rigidity of a deformity cannot be corrected without using measures to make the spine more compliant. In such instances, either an anterior or posterior release procedure is used to make the spine more flexible and enable correction. A more complex and extensive procedure, a posterior column osteotomy of the Smith-Petersen or Ponte type, involves the posterior removal of ligament and bone to partially correct scoliosis. The surgeon will also remove parts of the spinous process and facets and insert pedicle screws into the vertebral pedicles. The pedicle screws are used to hold a curved rod that mirrors the deformation of the spine of the patient. This curved rod has a personalized shape, which must be produced intra-operatively by the surgeon to ensure correspondence with the scoliotic curvature of the patient. Following the placement of this rod into its corresponding pedicle anchors, a 90-degree rotation is enacted to straighten out the spine. Even after a posterior release, such rotations require a significant amount of force, which is produced using rod holders that lock onto points along the curved rod. Knowing the amplitude of corrective forces prior to surgery would improve the surgical workflow by reducing the number and extent of releases performed, yielding a safer and more efficient surgery. While there are existing finite-element biomechanical studies for scoliotic surgery, the emphasis is placed on pedicle screw insertion mechanics instead of force determinants needed for full deformity correction (Cho et al., 2010, Bianco et al., 2015). Often, research conducted on the lumbar spine models ligaments as a set of one-dimensional rods whose anchor points are imposed by hand (Hortin et al., 2016). Additionally, patient-specific anatomical models that account for the interaction between vertebrae, bound to each other by ligaments, are generally not found in the literature or in clinical practice. Therefore, existing surgery planning and simulation does not provide accurate estimates of the amplitude of corrective forces necessary for scoliosis surgery. Updating state-of-the-art surgery simulation and planning are limited by two considerations. First, ligaments, especially spinal ligaments, are poorly delineated in both magnetic resonance imaging and computed tomography. Ligamentous tissue displays little contrast compared to other nearby soft tissue. Second, if ligamentous tissues were easily identified through segmentation, the tissue blobs would need to be processed into elements by volumetric meshing. Multi-material volumetric meshing as tetrahedra or hexahedra is not done in a manner that produces high-fidelity patient-specific models in the current state of the art.

1.3 Patient-Specific Modeling

The proposed anatomical modeling approach, founded on a deformable multi-surface model fitted to an anatomist-drawn Computer-Aided Design (CAD) template, can produce patient-specific finite element models for a number of applications in orthopedics. The emphasis for this portion of the study is the estimation of corrective forces in scoliosis surgery. The technique proposed addresses both segmentation and meshing, and warps the CAD model to any individuals' image dataset. Subsequently this guides multi-tissue high-fidelity two-stage tetrahedral meshing (Audette et al., 2007). The tetrahedralization approach consists of a surfacic first stage, from the discrete deformable surface model, to produce a controlled-resolution high-fidelity triangulated boundary, followed by a volumetric second stage of variational tetrahedral meshing at controlled-resolutions (Alliez et al., 2005). The volumetric stage uses a prescribed triangulated mesh boundary as an input, which is the resultant from the first stage. The deformable multi-surface model integrates the segmentation and initial meshing in one step. Validation can be achieved using cadaveric image studies, in which feature point clouds are identified by an anatomist and should coincide with the ligament boundaries.

1.4 Ontologies

Recent, concurrent developments have occurred in the fields of robot/computer-assisted surgery (RAS/CAS) and ontologies, which provide explicit concepts that guide surgical process modeling (SPM) (Lalys & Jannin 2014, Gibaud et al., 2018). Upper ontologies, a foundation of general terms consistent across all domains, are used to create surgical ontologies, which represent the various elements of knowledge that are contained by a surgical process (Mudunui 2009). Following the extraction of representations from upper ontologies such as the Basic Formal Ontology (BFO) or General Formal Ontology (GFO), elements of surgical ontologies may be utilized in CAS (Herre et al., 2006, Grenon & Smith 2004). The customized upper ontologies are formed into surgical ontologies, like LapOntoSPM, BISON, and Deep-Onto, all of which are used in the emerging domain of surgical data science and guide SPMs (Figure 1) (Katić et al., 2015, Siemoleit et al., 2017, Nakawala et al., 2018). These models can optimize the storage and querying of information related to pre/intraoperative data or images which impact the operation (Despinoy 2017, Kobayashi 2019). The widespread application of surgical process models for many, unique patients and their broad utilization is challenging due to limitations produced by the nature of surgical cases, the local surgical practices ontologies may be built upon, and disparities in vocabulary (Jannin & Morani 2007, Zaveri et al., 2012). To incorporate various ontologies for patient-specific interventions it is necessary to use a textual syntax resource description framework (RDF) file called a Terse Resource Description Framework Tripe Language (TURTLE), which enables data exchange within the semantic web (Berners-Lee & Jaffe 2018, Dunn & Markoff 2009). RDF is used to process metadata and provide interoperability between applications that exchange machine-comprehensible information. Ontologies, in Web Ontology Language (OWL), are a common framework for the semantic web, and may be understood to be a formal collection of terms. Subsequently, TURTLEs provide levels of compatibility within the N-Triples format and the triple pattern of SPARQL (SPARQL Protocol and RDF Query Language) to encompass the benefits of both ontologies and RDF files (Lassila & Swick 2018, Noy & McGuinnes 2001, Guarino et al., 2004). A TURTLE frames an RDF graph in a compact textual form, that is physician-readable and permits ontologies to be utilized in the RDF while maintaining the ontologies strict conceptualizations (Fetzer et al., 2016). TURTLE entities have the distinct triple format that follows <subject> <predicate> <object> [Lassila & Swick 2018]. In the context of surgical intervention, a surgeon is assumed to always perform the action, so the semantic web's Uniform Resource Identifiers (URI) are designated to the instrument that the surgeon will use and each instrument would have an attributed action, i.e. "pedicle screws" "implanted to" "vertebral pedicles" (specifically a physician-designated landmark).

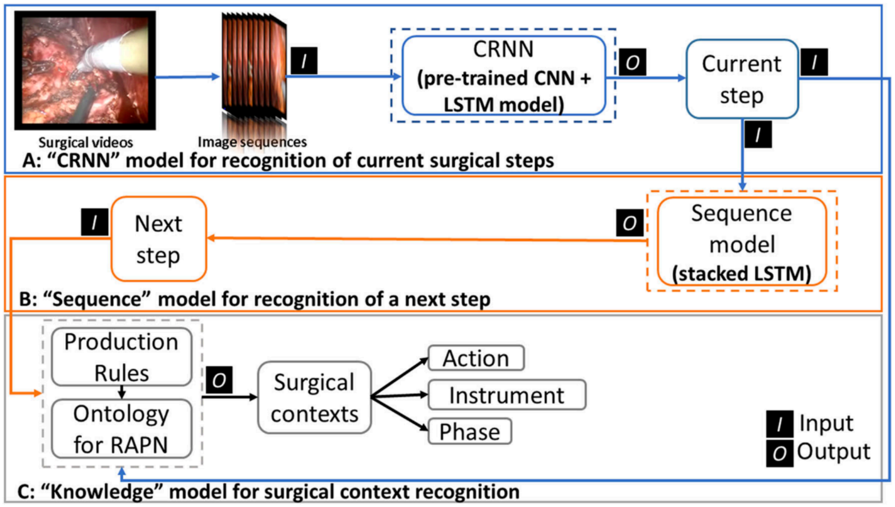


Figure 1: From the publication by Nakawala et al., 2018, this figure displays the potential use for surgical ontologies as a companion to surgical workflows and demonstrates the utilization of a surgical ontology in surgical process models.

1.5 Patient-Specific Model-Based Guidance

The first portion of this two component study encompasses the preliminary work on the completion of a deformable multi-surface methodology for the construction of ligamentous patient-specific anatomy, and displays preliminary results. Improvements will be made on this approach, which is founded on multi-material surface extraction that preserves shared anatomical boundaries of the patient. The main objective of this portion is to demonstrate the feasibility of using the model-image transformations undergone by vertebral surfaces of a descriptive torso model, drawn with CAD software by an anatomist, to be used as a basis for the nonrigid transformation of neighboring soft tissues, particularly ligaments. The second portion of this study harnesses upper level and surgical ontologies, which are maintained and coupled with physician-determined anatomical landmarks. Once merged, surgical ontologies and anatomical landmarks produce a TURTLE that includes a generic sense of shared surgical workflows, physician-designated information and patient-specific methodologies for surgical interventions (Tapp et al., 2019). These TURTLES yield more fluid SPMs and bridge the gap between the institution or geographic variations in surgeons' canonical approaches. Then, TURTLES are applied to the labeled patient-specific models, for use in CAS/RAS as seen in Figure 2 (Rubin et al., 2009, Carbonera & Abel 2015, Raimbault et al., 2003).

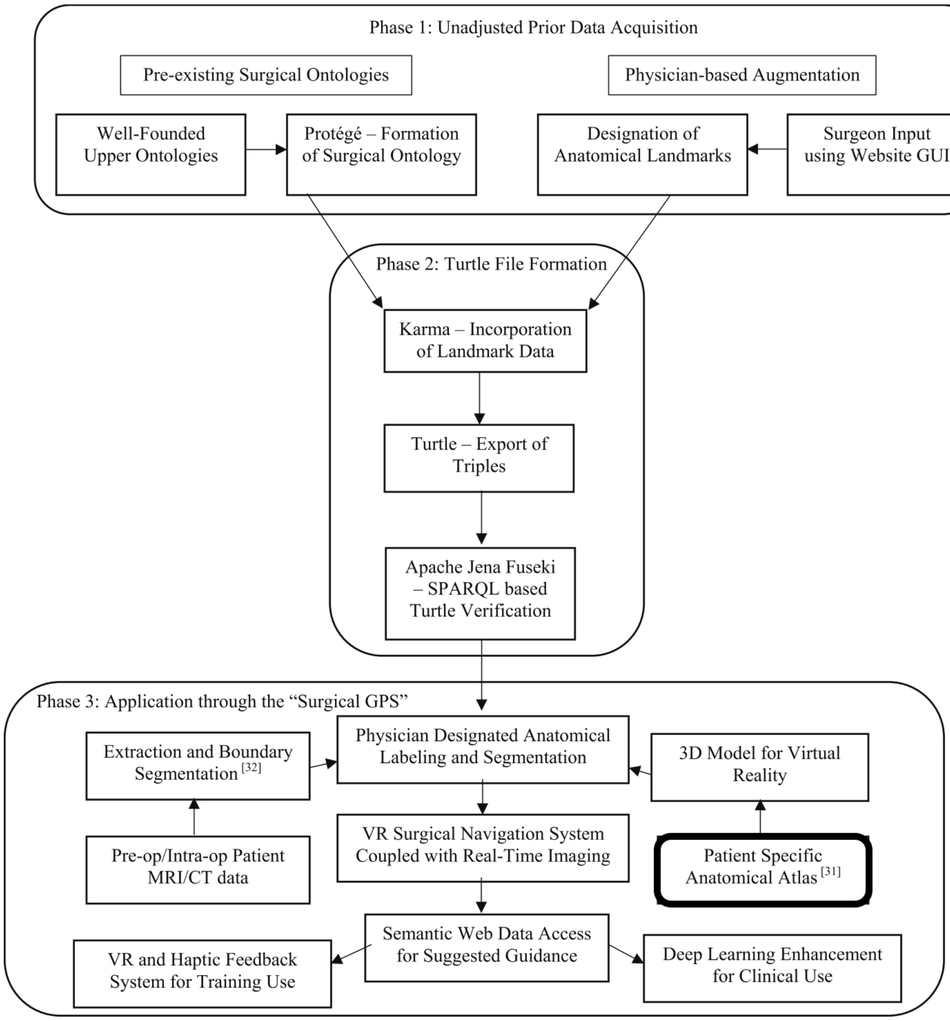


Figure 2: From the proceedings by Tapp et al., 2019, this figure displays the methodology behind the "Surgical GPS", from the production of TURTLES in phase 2 through the use of patient specific anatomical models in phase 3 (bold outline). This figure also highlights key differences between the types of anatomical landmarks used to generate a TURTLE, which can be either (1) generalized by the existing level of surgical ontologies, or (2) be made patient-specific through a determination by the physicians themselves.

2 METHODS

2.1 Converting Generic Anatomical Models

One major component in achieving descriptive personalized anatomical models of the spine is the use of CAD model of the full torso, which was purchased from CGHero (Figure 3)(https://cghero.com/). Because it is virtually impossible to volumetrically reconstruct the spinal ligaments from current routine imaging modalities using voxel-based segmentation techniques, a model of this kind is a necessary starting point. This resource permits a top-down, model-based segmentation approach, which naturally maps to the multi-surface anatomical atlas. As previously mentioned, current ligament representation is limited to a terse characterization based on hand-drawn linear constraints connecting one vertebral surface point to its opposing surface landmark. The ligaments are approximated as a simple collection of one dimensional springs or stiff rods. However, this methodology under represents the complexity of the constraining ligamentous geometry and reduces the fidelity of finite element studies. Finite element studies of the ligamentous spine should consider the constraining effect of the ligaments and this current spring/rod approach is limiting in relation to the complexity of the 3D ligament geometry. While it is preferred over an entirely untethered spine model, it is underwhelming and awkward in terms of user interaction. Additionally, the application of the material properties acquired by stress-strain experiments to a finite element model can be applied more appropriately compared to the current standard of springs or rods. These material properties can naturally feed into an anatomical model that mimics curviplanar or volumetric structures, depending on ligament thickness. The CGHero torso model, like all CAD drawings, is a collection of polygons, which are easily converted to a triangulated surface when each quadrilateral is bisected into two triangles. The new triangulated surfaces can be used to initialize a deformable surface model, such as the Simplex, through geometric duality. The Simplex production represents the foundational aspect of our workflow: (1) obtain the CAD B-spline surface model, (2) adjust the CAD into a triangulated surface, (3) convert the static triangulated surface to a deformable surface model, (4) make the surface patient-specific by warping the CAD model to the patient image. Such a conversion of a CAD model is surprisingly absent in literature and permits the use of the CAD drawing as a foundation for a deformable multi-surface model-based segmentation, particularly for musculoskeletal applications where ligamentous models are essential: orthopedics, obstetrics, etc. Extending the single-surface deformable model to include multiple anatomical boundaries is possible through Rashid's multi-surface methodology that emphasizes shared boundaries based on multi-material surface extraction (Rashid et al., 2017). This approach produces models of weight-bearing anatomy which maintain flush surfaces as needed. The methodology presented here can produce finite element models for other orthopedic applications, not just scoliosis surgical planning, and may significantly benefit the clinical community.

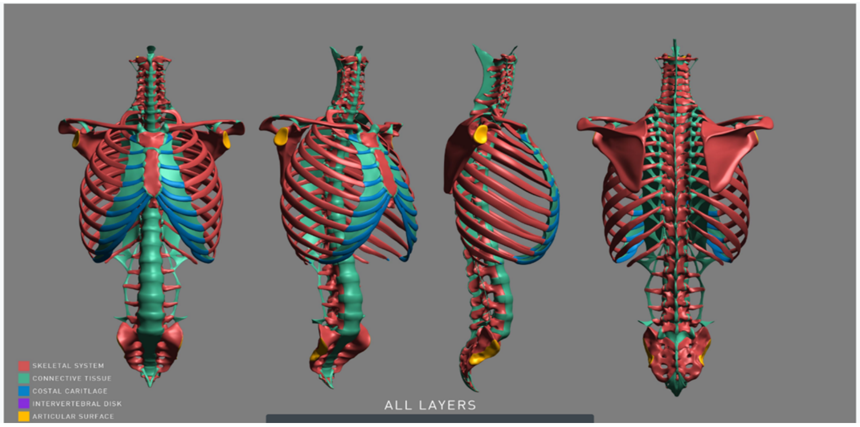


Figure 3: The CAD model of the torso, which includes soft tissues. This model was purchased from CG hero and was drawn by an anatomist. The model is broken down into individual components (bone, cartilage, ligament, IVD, etc.), all of which are represented by polygons and are stored in an .obj file format.

2.2 Patient-Specific Anatomical Models

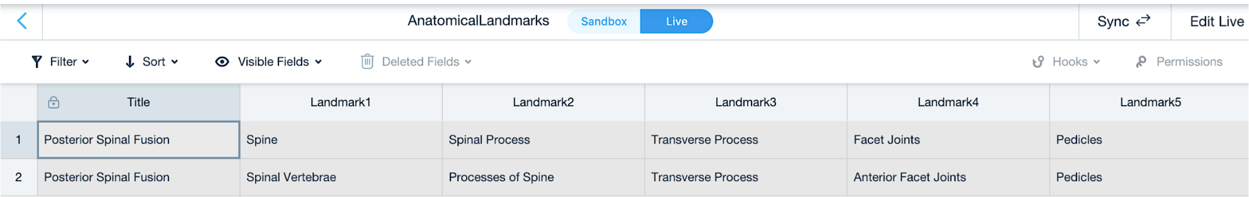
For this simple proof of concept, a target image of a healthy asymptomatic adult was obtained from the SpineWeb database. This base CT image is used to demonstrate the methodology cascade of vertebral model transformation, which is explicitly determined by sharp contrasts of the CT, and is used to drive the registration of nearby soft-tissue structures. While preserving the neighboring topology throughout, the contiguity of unambiguously registered vertebral surfaces constrain the positioning of soft tissue within the models. To initialize the model warping, a global affine transformation based on homologous point pairs is used. Then, a stable elastic transformation maps the CAD model of the vertebra onto the target boundary in the CT image. The same methodology describes the process for obtaining intervertebral disks (IVD) as a patient specific model; however, in this case, a MRI will be used instead of a CT image for the registration process. The culmination of these vertebral and IVD registrations will allow the soft-tissue surfaces to orient themselves to neighboring vertebrae. Again, the IVD and vertebral registration is not the innovation described in this paper, it is one foundational component of a the patient-specific surgical guidance project known as the "Surgical GPS". The deformable surface vertebral and IVD models can be aggregated to produce a registration of the ligaments. One option incorporates the models' points, leveraging them to determine a local transformation that is applied to a local neighborhood. Where the two warped vertebral models and two warped IVDs boundaries meet, a contribution may be made to the local elastic transformation applied to soft-tissue surfaces in the CAD model.

2.3 Ontology Instancing

A number of verified ontologies, like LapOntoSPM and BFO, were obtained from online repositories. It should be noted that while any OWL is compatible with Karma, a key data integration tool, these ontologies were chosen because they have extensive documentation and are used by many ontology development groups (Knoblock, Szekely, and Burns 2016). Additionally, both LapOntoSPM and BFO are founded on open biological and biomedical ontology principles (Grenon, Smith and Goldberg, 2004). Furthermore, a generically produced, non-unified and unverified ontology was created in Protegé to demonstrate the versatility of this type of data storage. The ontology that was created is based on information obtained from a variety of surgeons and surgical websites describing neurosurgical procedures (Cornejo et al., 2014). Each of the ontologies were created using Protege as previously described in "Ontology Development 101: A Guide to Creating Your First Ontology" and can be edited as needed (Noy & McGuinness 2001).

2.4 Integrating Surgical Landmarks

Currently, there are few ontologies and data repositories which describe physician-designated anatomical landmarks for surgical interventions. One exception is an anatomical ontology called The Foundation Model of Anatomy, but this ontology would require an extraction of the landmarks by the surgeons, depending on the surgical workflow. Additionally, other existing ontologies including FMA may not encompass the needs of that surgeon for a particular procedure (Noy et al., 2004). Some landmarks for posterior scoliosis correction surgery currently exist in a coarse manner on SurgicalWorkflows.com, however, the greater use of the site supports a positive feedback loop of surgical workflow description production (https://tappaustin.wixsite.com/surgicalworkflow). The landmarks used in a physicians' general workflow can be reused or updated by additional website users and are then stored in a database (Figure 4). The anatomical landmark values submitted are extracted as a comma-separated values spreadsheet, which can be seamlessly integrated into Karma (Knoblock, Szekely, and Burns 2016). Any existing ontologies, as an OWL format, are also integrated into Karma along with the physician's verified landmark entries. Users can connect the landmark information using links present from verified ontologies to form a completely new and unique SPM. Additionally, TURTLE files can be automatically produced by a predictive generation schema that is pre-built into the Karma software. The schema provides suggestions based on previous associations and records mapping history. The TURTLE files, since they exist in the RDF framework, should be checked using reasoners within Protege and Apache Jena Fuseki (HPLabs 2010, Apache Software Foundation 2011). Following the completion of this integration methodology, physician determined landmarks are now the RDFs third part of the triple, the <object>.



	Title	Landmark1	Landmark2	Landmark3	Landmark4	Landmark5
1	Posterior Spinal Fusion	Spine	Spinal Process	Transverse Process	Facet Joints	Pedicles
2	Posterior Spinal Fusion	Spinal Vertebrae	Processes of Spine	Transverse Process	Anterior Facet Joints	Pedicles

Figure 4: A screenshot of the database for stored anatomical landmarks values, which were designated by a physician for the posterior spinal fusion approach of scoliosis correction surgery. Row 1 displays the existing generic outline of procedural landmarks, while row 2 is updated to reflect additional flexibility.

2.5 TURTLES for Orthopedic Procedures

Anatomical landmarks submitted on the website's repository are associated with particular procedural parameters. An updated dataset will outline the suggested landmarks for the next website user who declares a similar patient situation. While the suggested landmarks appear, the physician has the ability to fully customize the procedural landmarks and actions. Additionally, a physician has the capability to produce a completely new custom landmark dataset for a unique procedure or procedures. The new submission can be officially ratified and displayed within the website for use by other physicians. For example, procedural adjustments may be made depending on the age, gender and curvature severity of a scoliotic patient. An updated set of landmarks would be common and expected for an 18 year old male patient compared to a 12 year old female patient. As many physicians provide greater amounts of patient detail, a continuous cycle for a significant number of surgical workflows and patient parameters can produce a wide range of repository data. This data can be integrated into existing ontologies, all of which would be verified by surgeon users. Additionally, methodologies associated with the action, also known as the <predicate> of the triple, are customizable. While more work needs to be done to appropriately incorporate the predicate into the TURTLEs, the potential for adjustments in these terms exists and can be updated for datasets using the same webpage. The TURTLE files produced are queried through SPARQL and may be introduced into the Apache Jena Fuseki server as single or multiple RDF models. The TURTLES as RDFs can be simultaneously uploaded, edited and manipulated. A SPARQL search extracts the <object> values and other data from the RDF model. Data between unknown relationships can be joined using this server, and landmark values can be interchanged for vocabulary purposes. Such terminological adjustment is a critical portion of anatomical landmark labeling used during surgical navigation. The Jena Fuseki server can annotate similar terms through the use of NeuroLex and SNOMED CT, which provide variable substitutions for terminology (Neurolex 2018). The terminology choices are incorporated into ontologies and published with unique resource identifiers specific to the approach, the patient and/or the surgeon.

3 RESULTS

3.1 Deformable Surface Model – Vertebra

At this stage, results and validation are qualitative rather than quantitative. A ground truth through expert segmentation of vertebrae and IVDs remains to be completed. Additionally, there is difficulty obtaining ground truth expert segmentations of the ligaments, which again are challenging to observe in CT or MRI alone. The preliminary results appear promising and provide support for the downstream methodology presented in the previous methods section. Figure 5 displays these results of the warped CAD model overlaid on the corresponding CT image. A validation strategy, possibly where ligaments sutured with MR and CT image detectable threading in cadavers, plans to be implemented. Using the detected thread as a point cloud sets which coincide with boundaries may be compared to the boundaries that are produced by the warped multi-surface model. Additionally, the use of shape statistics obtained from cadaveric studies may further enhance the robustness of the warped models, while employing static collision detection will prevent boundary overlap.

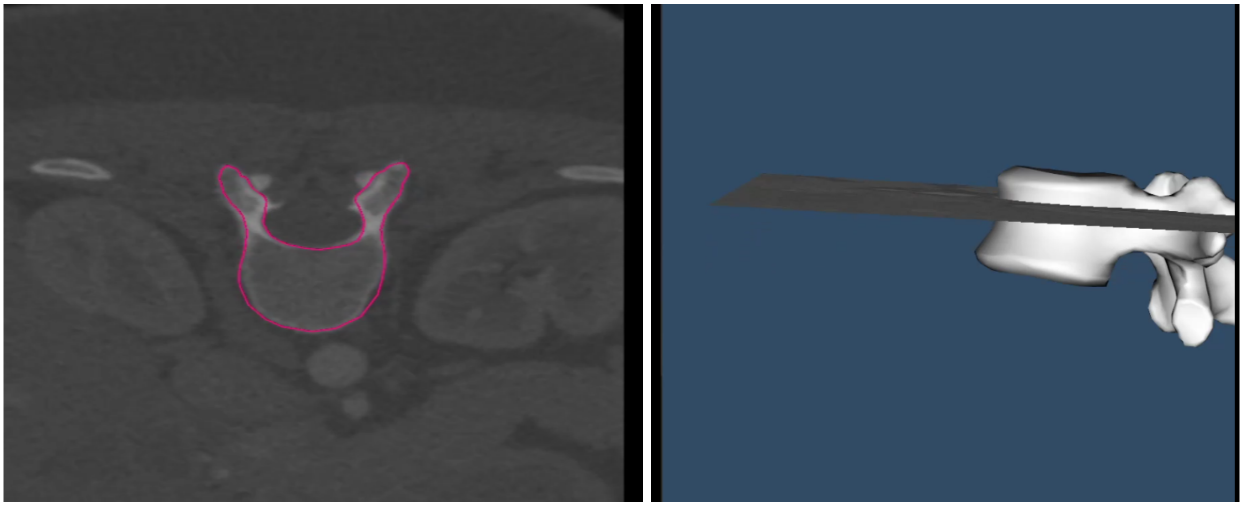
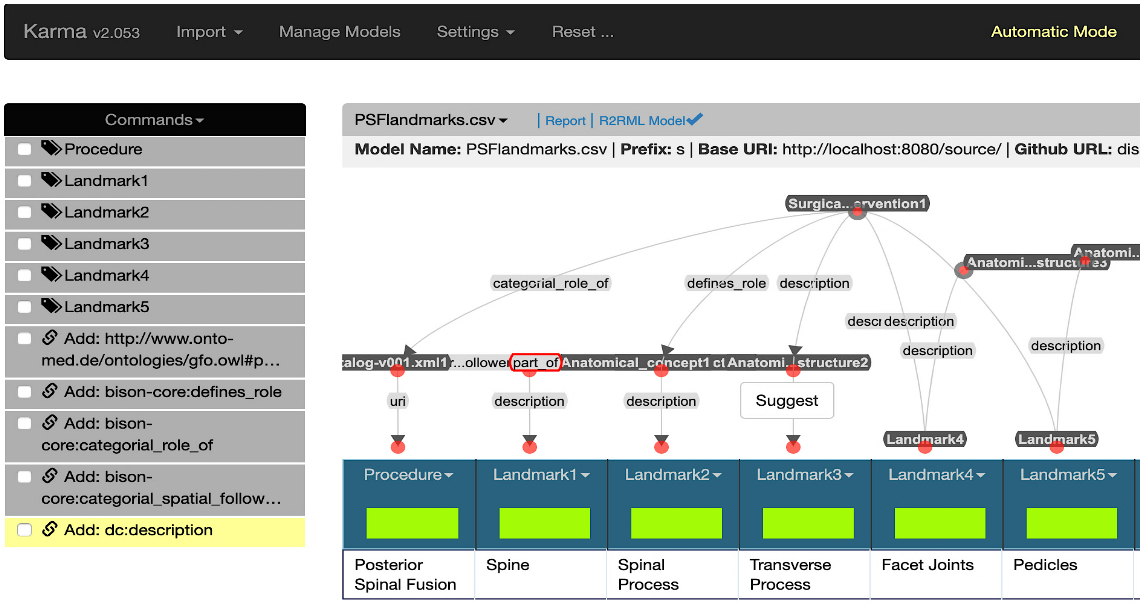


Figure 5: Screenshots of the warped CAD of the L1 vertebra overlaid on a transverse L1 vertebra CT image.

3.2 TURTLE Verification and Use

The BFO and LapOntoSPM ontologies downloaded were revalidated in Protege, as was the custom built ontology. These ontologies were adjusted as needed incorporated within Karma (Figure 6). The physician-determined anatomical landmarks imported as a comma separated values file were joined with the existing ontologies within Karma. Multiple SPMs were produced and successfully uploaded as RDF models into the Apache Jena Fuseki server for further use. In the case shown, the anatomical landmarks queried were submitted by physicians who had identified these waypoints as key landmarks to be noted as they move through the surgical corridor (Figure 7). These landmarks will be used to label and correspond with the anatomy of the patient-specific deformable surface model produced.



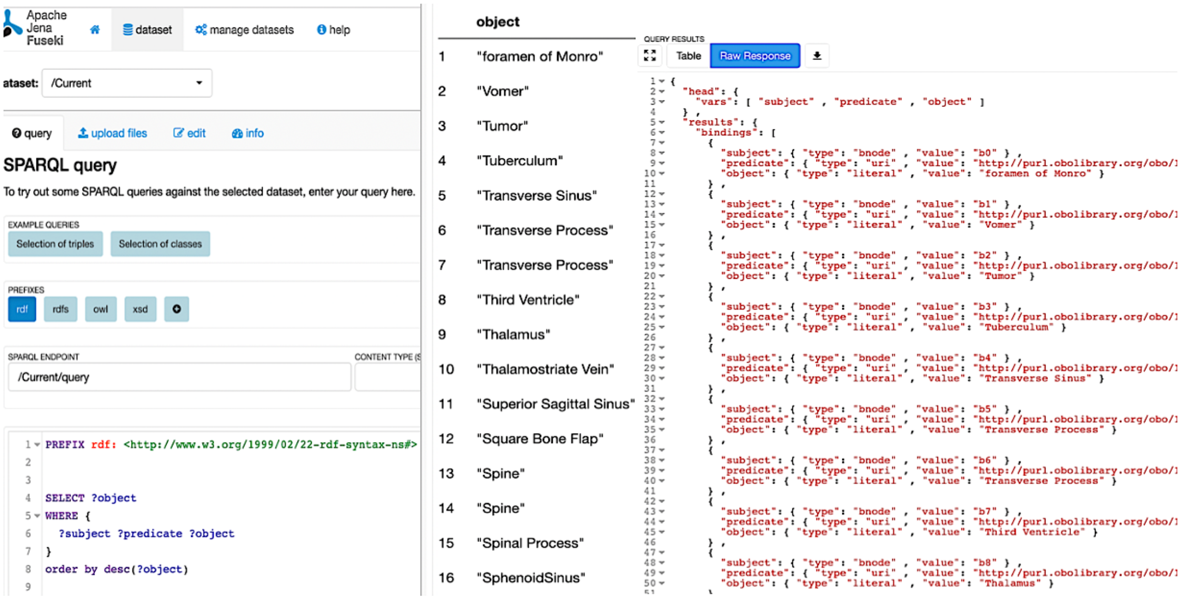
Model Name: PSFlandmarks.csv | **Prefix:** s | **Base URI:** http://localhost:8080/source/ | **Github URL:** dis

Procedure	Landmark1	Landmark2	Landmark3	Landmark4	Landmark5
Posterior Spinal Fusion	Spine	Spinal Process	Transverse Process	Facet Joints	Pedicles

Figure 6: A screenshot of Karma displaying the landmarks extracted from the website (seen in row 1 of Figure 4) that were incorporated with existing surgical and custom ontologies to ultimately produce RDFs.

3.3 “Surgical GPS” Proof of Concept

Following the labeling of the patient specific model with matching physician designated landmarks, the models may be utilized with intra-operative surgical guidance systems (Figure 8). The recognition of these landmarks intra-operatively can be accomplished through computer vision techniques after the unique resource identifiers produced innately by the RDF formation yields a seamless pathway from the model to the patient image. Regardless of the ontology that was utilized or the landmarks determined, even if sham landmarks are declared, the surgical workflow production system proposed here may build any surgical process models that can be queried by CAS/RAS systems. Additional model exploitation may be achieved by uploading and editing TURTLES simultaneously within the Apache Jena Fuseki Server. Multiple TURTLES for a variety of procedures can be utilized as a single landmark dataset. This rapid integration provides support for operations performed by multiple surgeons, or those procedures that might necessitate immediate action, such as orthopedic trauma surgery followed shortly by plastic surgery. In this instance, two differing surgical processes might need to be conjoined to provide one, accentuated workflow based on individual physician submission preferences of particular anatomical landmarks. This aggregation may even occur if the TURTLE files are produced and uploaded independently onto the server. Many other procedures, including ontologies for nurses who may be preparing the patient, can be conjoined in this way to produce a single solid workflow of queryable data that would not need or require multiple files after instantiation. Augmenting the workflow of patient care from preoperative to postoperative status would drastically enhance the ability of healthcare providers throughout an institution.



ataset: /Current

SPARQL query

To try out some SPARQL queries against the selected dataset, enter your query here.

SPARQL ENDPOINT: /Current/query

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>


SELECT ?object
WHERE {
  ?subject ?predicate ?object
}
order by desc(?object)

```

	object
1	"foramen of Monro"
2	"Vomer"
3	"Tumor"
4	"Tuberculum"
5	"Transverse Sinus"
6	"Transverse Process"
7	"Transverse Process"
8	"Third Ventricle"
9	"Thalamus"
10	"Thalamostriate Vein"
11	"Superior Sagittal Sinus"
12	"Square Bone Flap"
13	"Spine"
14	"Spine"
15	"Spinal Process"
16	"SphenoidSinus"

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{
  "head": {
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  } ,
  "results": {
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        "object": { "type": "literal" , "value": "Thalamus" }
```

Figure 7: A screenshot of the SPARQL search of an RDF using a specific filtering script (left) that returns the results as a series of anatomical landmarks <objects> (center) as well as the raw TURTLE file (right).

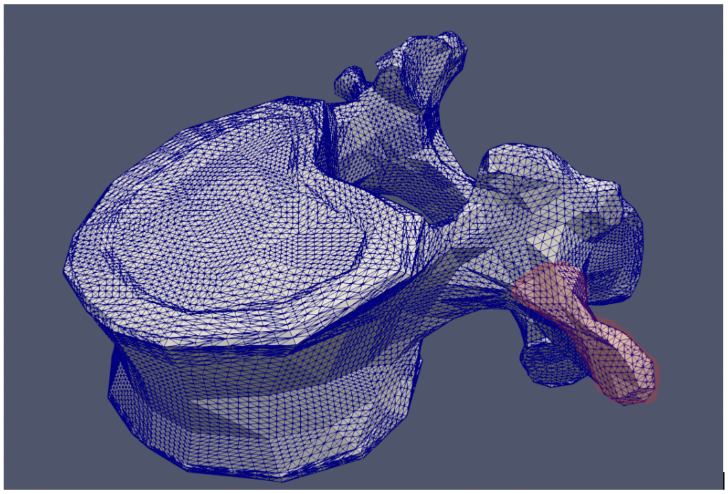

Figure 8: A screenshot of the patient specific model produced by the registration of the CAD model onto the patient image. The labeling of various portions of the model with matching physician designated landmarks can simultaneously drive SPMs and allow for surgical guidance. In this instance, the transverse process has been highlighted red to represent that was designated as an anatomical landmark of interest.

4 DISCUSSION

4.1 Conclusion

At this stage, our two component study encompasses the preliminary work on the completion of a deformable surface model that is patient specific and its ability to be labeled for subsequent use by surgical process models for computer assisted surgery. Presented were two critical aspects of the overall "GPS": (1) a novel approach to producing personalized anatomical models of the spine that emphasizes ligaments in order to yield a finite elements simulation for scoliosis surgery planning, and (2) an innovative methodology for the incorporation of context-aware surgical interventions through the use of physician-designated anatomical landmarks. While the meshing methodology is not unique, the application of anatomist-drawn CAD models is new and broadly applicable to any type of surgery planning. This method will only benefit from the enhancement of imaging modalities which may soon delineate the ligaments and other soft tissues. Further, the use of physician augmented surgical process models can be frequently adapted to match the specificities of the surgeon and the patient. To fit these adaptations in a rapid and easily reproducible way, existing surgical ontologies are merged with the anatomical landmarks of interest using Karma. The landmark information can be stored for recommendations and will accept new landmark values that better fit a particular intervention. The use of community-verified surgical ontologies and textual anatomical landmarks placed upon a patient specific atlas provides enhanced and individualized healthcare.

4.2 Future work

Additional approaches for shared boundaries will be explored to better develop a shared-boundary deformable multi-surface model that includes IVD-vertebra and ligament-vertebra interfaces which should remain in perfect contact throughout the deformation. Furthermore, the enhancement of the SurgicalWorkflows.com website and the development of the online surgical community is a necessity for this project. The incorporation of all types of specialty data into the website will provide a groundwork for improving all potential procedures. This process has already begun with the elucidation of methodologies for neurological and orthopedic surgery. It will also be necessary to enhance the framework that allows for the unstructured submission of anatomical landmarks for larger and more detailed procedures, as to not limit the surgical community by the pace of the website's development. The ultimate purpose of this work is the completion of an individualized healthcare workflow, for now, termed the "Surgical GPS".

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