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Medical image computing in diagnosis and intervention of spinal diseases

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ABSTRACT

Spinal image analysis and computer assisted intervention have emerged as new and independent research areas, due to the importance of treatment of spinal diseases, increasing availability of spinal imaging, and advances in analytics and navigation tools. Among others, multiple modality spinal image analysis and spinal navigation tools have emerged as two keys in this new area. We believe that further focused research in these two areas will lead to a much more efficient and accelerated research path, avoiding detours that exist in other applications, such as in brain and heart.

The spine represents a vital central axis for the musculoskeletal system and a flexible protective shell surrounding the most important neural pathway in the body, the spinal cord. Diseases of the spine are very common, affecting up to 80% of the population worldwide, and may cause pain, disability and economic loss. Back pain ranks seventh among the costliest health conditions, only preceded by heart disease, diabetes, hypertension, stroke-related conditions, osteoarthritis and pneumonia, and its global burden is projected to increase markedly in the next few decades with the aging of the world population.

For diagnosis and treatment of many spine related diseases, imaging is often required. Different modalities such as plain radiographs, CT, MR, ultrasound, and nuclear medicine provide complementary information regarding both anatomy and physiology. The evidence supporting this complementarity has been gained over the last few years with increased interests in the development of platform hardware for multimodality imaging. Images of different modalities are now increasingly integrated within both diagnostic and therapeutic patient management.

The field of medical image computing and computer assisted interventions has been playing an increasingly important role in diagnosis and treatment of spinal diseases during the past twenty years. Specifically, medical image analysis ensures the derivation of optimized parameters from the acquired multimodality spinal images, allows for exploitation of these image-derived parameters, and facilitates the development of anatomical and associated physiological models which can further help in understanding different spinal disease mechanisms. Most importantly, the combination of these models with multimodal images, sensory data from spatial tracking or force sensors, visual displays, or other feedback systems will facilitate personalized therapy. For example, although different techniques of pedicle screw placement have been described in the past, none of these techniques reduced the incidence of malpositioned pedicle screws significantly until the technical problems of integrating image information, spinal anatomy, and the action of surgical instruments via real time computing were solved by 1995, leading to the first report on the successful clinical application of an image guidance system for pedicle screw placement in lumbar spine [1]. Since then, there has been a trend toward multimodality imaging and the adoption of surgical navigation in management and treatment of various spinal diseases. This trend has presented significant opportunities but also reveals certain pitfalls.

The spinal column consists of thirty-three vertebrae and is divided into seven cervical, twelve thoracic, and five lumbar vertebrae. The lumbar vertebrae articulate with the sacrum, which in turn articulates with the pelvis. The articulations of spine are based on synovial and fibrocartilaginous joints. The overall morphology of the vertebral column has a basic similarity, with the exception of the first two cervical vertebrae and the sacrum. Thus, compared to

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other anatomical structures, the spine poses additional challenges to quantitative image analysis as it consists of an array of vertebrae where the individual vertebrae show a complex shape. Although the shape of the individual vertebrae changes significantly along the spine, most neighboring vertebrae look very similar and are difficult to distinguish.

Diagnosis and treatment of spinal diseases, such as degenerative disc disease, osteoporosis, scoliosis, fracture, spine metastasis, or spondyloarthropathy, often require integrated quantitative analysis of spinal images of multiple anatomic structures in multiple anatomical planes from multiple imaging modalities (M^3) [2]. This poses a great challenge to both manual processing and automated processing methods. First, manual processing is bound to be infeasible for M^3 images because of its known tediousness, inefficiency, and inconsistency; for example, it takes an operator up to 15 min to assess vertebral fracture (an indicator of osteoporosis) even in a single spinal image of one specific structure, in one specific plane or from one specific modality (S^3). Second, computer processing methods have achieved preliminary success in processing S^3 spinal images efficiently and consistently, although they are still unable to handle M^3 images since automatic vertebra recognition and segmentation within a framework is extremely challenging due to the M^3 diversity including: (a) totally different appearances of different structures, such as vertebra and disc; (b) completely different intensity profiles from different imaging modalities, such as MRI, CT, and X-ray; and (c) substantially different shapes in different planes, such as sagittal and axial even for the same anatomic structure. Such diversity brings challenges on multiple levels to the conventional vertebra recognition and segmentation methods.

Because multimodality images by definition contain information obtained using different imaging methods. They introduce new degrees of freedom, raising questions beyond those related to exploiting each single modality separately. Processing M^3 images is then all about enabling modalities to fully interact and inform each other. It is important to choose an analytical model that faithfully represents the link between the modalities without imposing phantom connections or suppressing existing ones. Very little is known about the underlying relationships between images acquired from different modalities even when those images are acquired from the same patient. Hence, it is important to be as data driven as possible. In practice, this means making the fewest assumptions and using the simplest model, both within and across modalities. Example models include linear relationships between underlying latent variables, use of model-independent priors such as sparsity, non-negativity, statistical independence, low-rank, and smoothness, or both. Such a principle has been successfully applied to solving challenging problems in a variety of spinal applications including vertebra recognition [2], intervertebral disc localization and segmentation [3], and vertebra segmentation [4].

For multimodality spinal image computing, we now enter a “Big data” era, in which the abundance of diverse imaging modalities makes it practically impossible to ignore the presence of multiple datasets that are possibly related. It is very likely that an ensemble of related datasets is more than the sum of its parts, in the sense that it contains precious information that is lost if these relations are ignored. Despite the evident potential benefit, the knowledge of how to actually exploit the additional diversity that multimodality images offer in spinal imaging is currently at its very preliminary stages and remains open for exploration.

Meanwhile, spinal instrumentation has undergone significant advances in the last two decades, with transpedicular constructs now widely used in spinal fixation. Pedicle screw constructs are routinely used in thoracolumbar-instrumented fusions, and in recent years, the cervical spine as well. Anatomical landmarks and fluoroscopy may have been used routinely for pedicle screw insertion, but a number of studies reveal inaccuracies in placement using these conventional techniques. The ability to combine three-dimensional (3D) imaging with intraoperative navigation systems has improved the accuracy and safety of pedicle screw placement, especially in more complex spinal deformities [1]. Image-guided surgery systems comprise a closely related group of technologies that fuse preoperative or intraoperative images with 3D localization of surgical instruments in real time. Using surgical navigation methods, physicians may make more accurate pedicle screw placement. Advanced technologies provide computerized, 3D viewing so that physicians and surgical teams can precisely locate and position surgical instruments in the surgical field and view the results on their visual displays. As a result, procedures are shorter and protocols are improved. Surgical navigation may also be less invasive than traditional surgery as surgeons may be more accurate using technologically advanced devices in place of the traditional hand-guided, mechanical devices during surgery. This allows for an increased level of patient safety and an overall reduction in patient morbidity. In addition, recent enhancements to surgical navigation technology have enabled new and even less invasive procedures.

A spinal navigation system utilizes an image-guided surgery system coupled with varying imaging modalities. Pre-operative CT images or intra-operative images, such as 2D fluoro images from a C-arm or cone beam CT (CBCT) images from portable, rotational devices such as the O-arm (Medtronic Sofamor Danek, Memphis, TN, USA), may be used. In all uses, the combined system provides real-time updates of instrument location and trajectory in reference to the operative images. In the case of pre-operative CT, the patient is registered to the images through a manual method of picking common points or common features on the image and on the patient. In the case of intra-operative imaging, the images obtained in the operating room are automatically registered to the patient without any surgeon intervention required.

Despite its touted advantages, such as decreased radiation exposure to the patient and the surgical team, increased accuracy in most situations, and elimination of the surgical field from the C-arm fluoroscopy, spinal navigation has yet to gain general acceptance among spine surgeons. Although issues related to training, technical difficulty, and learning curve are commonly presumed to be major barriers to the acceptance of spinal navigation, a recent study [5] suggested that surgeons did not select them as major weaknesses. It has been indicated that barriers to adoption of spinal navigation are neither due to a difficult learning curve nor to a lack of training opportunities. The barriers to adoption of navigation are more intrinsic to the technology itself, including intraoperative glitches, unreliable accuracy, frustrations with intraoperative registration, and line-of-sight issues. These findings suggest that significant improvements in the technology will be required to improve the adoption rate of spinal navigation. Addressing these issues from the following perspectives may provide solutions in the continuing effort to implement spinal navigation in everyday clinical practice.

- **2D or 3D image stitching**: Spinal deformity correction is a type of surgery that frequently uses the C-arm in its operation. Such a surgery usually involves corrective maneuvers to improve the sagittal or coronal profile. However, intraoperative estimation of the amount of correction is difficult, especially in longer instrumentation. Mostly, anteroposterior (AP) and lateral fluoroscopic images are used but have the disadvantage to depict only a small portion of the spine in a single C-arm image due to the limited field of view of a C-arm machine. As such, spine surgeons nowadays are missing an effective tool to image the entire spine during surgery for assessing the extent of correction in scoliotic deformity. Although radiographs, obtained either by using a large field detector or by image stitching, can be used to image an entire spine, they are usually not available for intraoperative interventions. One alternative is to develop methods to stitch multiple intraoperatively acquired small fluoroscopic images to be able to display the entire spine at once [6,7]. The same idea can be extended to 3D imaging to create a panoramic cone beam computed tomography [8]. At this moment, fast and easy-to-use 2D or 3D image stitching systems are still under development and as the technology evolves, it is expected that surgical benefits and clinical outcomes will improve further.

- **Image fusion**: Fusion of multimodality preoperative images such as various MRI or CT datasets with intraoperative images would allow for visualization of critical structures such as nerve roots or vascular structures during surgical navigations. Thus, multimodality spinal image analysis as described above plays an important tool in spinal navigation. However, due to the articulation characteristics of the spine, the rigid registration based image fusion algorithms, which are readily available in cranial procedure, have limited capability in the spinal procedure; more advanced algorithms using articulated models are being investigated [9,10].
- **Biomechanical modeling**: It is important to incorporate biomechanical simulation and modeling into the surgical decision making process. For example, a large spectrum of medical devices exists for correcting deformities associated with spinal disorders. Driscoll et al. [11] developed a detailed volumetric finite element model of the spine to simulate surgical correction of spinal deformities and to assess, compare, and optimize spinal devices. Another example was presented in [12] where the authors showed that with biomechanical modeling, the instrumentation configuration can be optimized based on clinical objectives. Incorporating this type of patient specific biomechanical modeling into spinal navigation may eventually increase the quality of surgical outcomes [13].
- **Spine robotics**: At present two commercially available systems, the Da Vinci (Intuitive Surgical Inc., Sunnyvale, USA), which is originally developed for minimally invasive endoscopic procedures) and the SpineAssist (Mazor Robotics Ltd., Israel) have been assessed for spinal procedures. Although both systems are FDA- and CE-approved, these two systems follow a completely different philosophy. The Da Vinci translates the surgeon's movements and manipulations to the surgical field via robotic arms without any form of image guidance whereas the SpineAssist is an image-guidance system leading the surgeon to pre-planned trajectories for spinal instrumentations leaving the surgical steps in the hand of the surgeon [14]. The application of image-guided robotic assistance to spinal procedures has the advantages to enable surgeons to visualize and navigate complex anatomic structures during planning and execution stages and to provide critical support for minimally invasive surgical (MIS) procedures with accuracy improvement and decrease of the incidence of neurological deficits. As spine procedures commonly require fine manipulation of critical structures that are often accessed through minimally invasive key hole surgery, they are ideally suited for the integration of robotic assistance.
- **Patient-specific guide:** Patient-specific drill template using 3D printing technologies have been applied as a relatively simple and effective navigation solution to improve the accuracy of screw placement in spinal surgery [15]. With such a technique, the line-of-sight issues in the optical surgical navigation systems can be completely eliminated. One of the critical steps for a successful use of the image-based drill template is the optimal design of the patient-specific template which is largely dependent on the 3D image segmentation quality. Roust, accurate and efficient spine CT segmentation algorithms are being investigated [16].

In summary, the field of medical image computing in diagnosis and intervention of spinal diseases is still in its infancy, despite the fact that several techniques have been successfully applied in a number of spinal applications in clinics. Many more opportunities will emerge in diagnosis, staging, treatment and disease monitoring in the foreseeable future. Leveraging on the multiple modality analysis and navigation tools, spinal applications will be able to avoid the detours that hinder other applications such as those in the heart; they will be able to accelerate the translation of current research into clinics based on recent advances of machine learning, information and sensor fusion. We believe that further development in multimodality spinal image computing and spinal navigation will lead to the next generation of technologies and procedures that will tremendously improve clinical outcomes, minimize patient risks and morbidity, decrease procedure time, and ultimately reduce healthcare costs. We hope that this perspective paper will provide an impetus for this growing field of research.

Conflict of interest

The authors have no conflict of interest related to this work.

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