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Innovative approach in the development of computer assisted algorithm for spine pedicle screw placement

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ABSTRACT

Pedicle screws are typically used for fusion, percutaneous fixation, and means of gripping a spinal segment. The screws act as a rigid and stable anchor points to bridge and connect with a rod as part of a construct. The foundation of the fusion is directly related to the placement of these screws. Malposition of pedicle screws causes intraoperative complications such as pedicle fractures and dural lesions and is a contributing factor to fusion failure. Computer assisted spine surgery (CASS) and patient-specific drill templates were developed to reduce this failure rate, but the trajectory of the screws remains a decision driven by anatomical landmarks often not easily defined. Current data shows the need of a robust and reliable technique that prevents screw misplacement. Furthermore, there is a need to enhance screw insertion guides to overcome the distortion of anatomical landmarks, which is viewed as a limiting factor by current techniques. The objective of this study is to develop a method and mathematical lemmas that are fundamental to the development of computer algorithms for pedicle screw placement. Using the proposed methodology, we show how we can generate automated optimal safe screw insertion trajectories based on the identification of a set of intrinsic parameters. The results, obtained from the validation of the proposed method on two full thoracic segments, are similar to previous morphological studies. The simplicity of the method, being pedicle arch based, is applicable to vertebrae where landmarks are either not well defined, altered or distorted.

1. Introduction

In thoracic deformity correction surgery the use of pedicle screws is becoming largely adopted [1] despite the intraoperative complications such as pedicle fractures (13%), dural lesions (12.1%) and the postoperative fusion failure (4.3%) [2]. Hicks et al. [3] performed a systematic review of 12248 pedicle screws and found that 4.3% were reported as malpositioned. In the short term malpositions are asymptomatic, and the actual percentage of such irregularity is often underestimated. In fact, this percentage is estimated to be higher than 15.7% if Computed Tomography (CT) is used to evaluate the screw placement. Using CT, Privitera et al. [4], performed another study examining 1042 screws and reported 8.3% to have been misplaced, with the upper thoracic levels T1 and T2 showing the highest malposition rates of 28.6% and 18.2%, respectively. Cardoso, using CT scans, identified the structures at risk of screw malposition placement [5]. Complications were seen in the esophagus (greater at T2), trachea (greater at T3) and Bronchus (greater at T4). To limit the malposition rate, computer-assisted spine surgery (CASS) and patient-specific drill templates were developed. Verma et al. [6] reviewed 23 studies from 1997 to 2007 for a total of 5992 pedicle screws and found that pedicle screws implanted by CASS had greater accuracy than conventional placement technique. Furthermore, he found that the neurological complications using CASS were less but not statistically significant ($p = 0.07$). In another study, Lu et al. [7], using patient specific templates of 16 scoliosis patients, found that only 1.8% of the screws were misplaced, and most of the screws were safe. Despite the accuracy achieved with CASS or patient specific templates, the trajectory of the screws remains at the discretion of the surgeon. The planning is mostly performed on 2D CT-based images combined with basic manipulations and generic anatomical markers/indicators (Fig. 1) [7,8].

In the past, anatomical studies have been performed focusing on the identification of the screw insertion site and the proper screw trajectories for better fixation and reduction in breaching.

Lehman et al. [9,10] differentiated between a straight-forward insertion in which the sagittal angulation of the screw is parallel to the superior endplate of the vertebral body, and an anatomic insertion trajectory, that follow the sagittal angle of the pedicle axis at a convergent angle of 22°.

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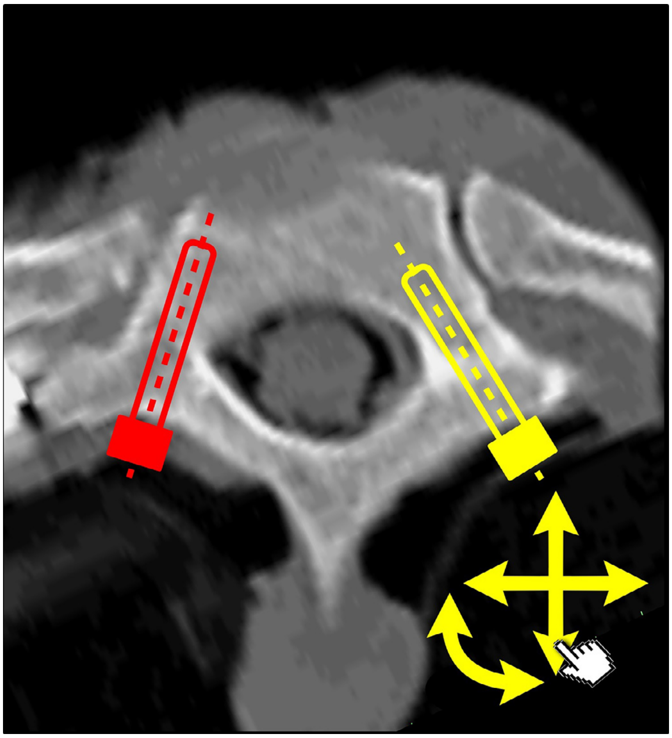

Fig. 1. 2d visualization of screw placements on axial CT image of T1.

The straight-forward technique was later used by Kim [11], where the insertion point is presumed to move more lateral and caudal from T12 to T1 with an average convergent transverse angle of 15.3°. Using the anatomical technique without image guidance, Elliot achieved full pedicle containment of the 5 mm screws in only 87.5% of the specimens [12].

A more focused study on the screw placement angulation was performed by Zindrick et al. [13]. They reported transverse angle variation from a convergent value of 26.6° ± 5.6° at T1 to a divergent value of 4.2° ± 9.5° at T12, and a variation of sagittal angle from 12.6° ± 5.8° at T1 to 11.6° ± 2.6° at T12. Similarly, Lien et al. [14] using CT data and cadaveric dissections, reported an average pedicle transverse convergent angle of 28.6° at T1 that progressively decreases to 7.9°. Furthermore, he found that the pedicle safe zone dimension has a maximal width of 8.5 ± 1.5 mm at T12 and a minimal width of 3.4 ± 0.6 mm at T4. A first analytical approach has been adopted by Rampersaud et al. [15] to evaluate the required screw placement accuracy. Both pedicles and screws are modeled using cylinders with a dimension of 5 mm for the screws and average diameter value computed from 24 morphological studies. Rampersaud found that the allowable distance from the central axis of the pedicle varied from 1.5 mm at T1 to 0.5 mm at T12 with a virtual minimum of –0.05 mm at T5. The allowable angular deviation from the pedicle axis varied from 7.7° at T1 to 2.5° at T12.

The variability highlighted in these studies indicates the need of an algorithm that can be used and adopted on a case-by-case basis. Such algorithm is specifically needed, in cases where the distortion of anatomical landmarks limits the applicability of previous morphological studies [16].

This paper aim is to automate and significantly reduce the time of surgical planning, through the execution of sequential steps, for a given vertebra, identifying the screw trajectories and calculating the parameters, which yield the optimum screw insertion trajectory. The calculated trajectories are provided in an output format defined by the position of the entry point and its orientation, and can be used with CASS, patient specific templates and free hand approach.

2. Methods

2.1. Algorithm framework

The overall framework of the methodology developed for pedicle screw insertion is shown in Fig. 2. It is divided into several steps where the blocks define the local computation and analysis required to proceed or interface with the others. The method makes use of data that is commonly available to clinicians/surgeons. The main computer-assisted tasks are identified in the following steps: reference frame and region of interest identification (ROI), cross sections discretization, trajectories calculation, safe trajectories filtering, numerical parameters calculation and selection. What follows is the description to each of the steps outlined above.

2.2. Reference frame and identification of the region of interest

The algorithm uses 3D surface reconstructions (imported as triangulated surfaces in STL format) of both the cortical (S_c) and trabecular (S_t) bones obtained from CT scan segmentation with a threshold intensity as defined by Rathnayaka et al. [17] targeted to estimate the cortical bone thickness [18]. For each vertebra a reference frame is assigned with a transverse plane ($\pi_t \equiv x\text{–}y$) as the bisector plane for the two endplates, frontal plane ($\pi_f \; // \; x\text{–}z$) perpendicular to the transverse plane, and a plane parallel to the plane passing through the left and right upper edges of the posterior wall of the central vertebra [19]. This is illustrated further in Fig. 3a where we drew a sagittal plane ($\pi_s \equiv y\text{–}z$) perpendicular to these two planes containing the center of the vertebral foramen.

A surgeon is usually asked to identify the pedicle screw dimensions such as: length (l), external (d_{ext}) and core (d_{core}) diameters and two planes identifying the clearance between the screw tread surface and the external bone layer. The two planes, characterizing the pedicle section and the entry region are identified by the sagittal positions d_p and d_e as well as the rotation angles α_p and α_e around the z-axis (see Fig. 3b).

The first section plane (π_p) should be positioned to correspond to the smallest cross section area of the pedicle whereas the second plane (π_e) should be positioned proximal to the triangular region formed by the superior articular process, the transverse process, and the pars inter-articularis [20]. The latter is largely adopted for localizing the placement of the pedicle probe [21,22]. The resulting planes are expressed as follows:

$$\pi_e \rightarrow \sin(\alpha_e)x + \cos(\alpha_e)y = \cos(\alpha_e)d_e \tag{1}$$

$$\pi_p \rightarrow \sin(\alpha_p)x + \cos(\alpha_p)y = \cos(\alpha_p)d_p \tag{2}$$

The Region of Interest (S_{ROI}) in the posterior arch is now defined as the volume of the hemi vertebra portion ($S_c \cap {\pi_s}^+$) limited in the anterior direction by the plane defined by the pedicle (π_p), and in the caudal direction by the plane (π_{pt}) which is parallel to the transverse plane (π_t). The latter is a plane passing through the inferior edge of the pedicle section ($P_p = min_z(\Gamma_p = (S_c \cap {\pi_s}^+) \cap \pi_p)$) in the transverse plane z direction, and is limited in the lateral direction by a cylindrical surface (S_{cil}) with cranial direction, surrounding the articular facets, with the aim of removing the transverse process (Fig. 4a).

The surface S_{cil}, contains the highest point of the superior articular facet ($P_a = max_z(S_c \cap {\pi_s}^+)$) and is defined introducing a user-defined distance (d_c). This is given by

$$S_{cil} \rightarrow x^2 + y^2 = \left(d_c + \sqrt{\left(P_a \cdot \hat{x}\right)^2 + \left(P_a \cdot \hat{y}\right)^2} \right)^2. \tag{3}$$

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