

COMPUTED AIDED DESIGN OF 3D TEMPLATE FOR PEDICLE SCREW TRAJECTORY IN THORACIC VERTEBRAE

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ABSTRACT

Pedicle screw fixation is one of the commonly employed orthopedic surgeries due to its enhanced biomechanical advantages. However, this method is limited by the accurate placement of the screw which is often dependent on the technical expertise of the surgeon. In addition, improper fixation of the pedicle screw often results in vascular, neurological, and visceral injuries. Hence, there is a need to simulate the pedicle screw fixation preoperatively. In this study, a pedicle screw template is developed in the thoracic vertebrae (T12 region) to assess the accurate placement using CT images. The T12 region is segmented from the CT images using Materialize MIMICS innovation suite (v21.0). Using AutoCAD, the 3D pedicle screw is developed for the segmented T12 vertebrae. The simulated CAD model pedicle screw is then imported into MIMICS software and the fitting of the pedicle screw into the lamina region is evaluated. In addition, a pedicle screw navigation template is developed for the T12 thoracic vertebrae. The pedicle screw diameter and length are determined as 7 mm and 38 mm. The fitting of the developed pedicle screw model into the lamina region is evaluated and the simulation of screw insertion is assessed using MIMICS software. By this method, it is possible to measure accurate pedicle screw length and diameter from preoperative or intraoperative CT scans in real-time, thereby we can customize the pedicle screw navigation template based on the subject's anatomical preference. Thus, this study aid in less neurovascular complications increased placement accuracy, and reduced plan time.

Keywords:

Pedicle screw fixation, Thoracic vertebrae, MIMICS, T12 region, AutoCAD

INTRODUCTION

Even though pedicle-screw fixation is considered the golden standard for internal spinal fusion technique (4), it is also subjected to considerable muscle dissection because of its greater anatomical bony area involvement (5), and screw loosening (6). The fixation technique involves posteriorly inserting the pedicle screw into the vertebral body through the narrow and long pedicle. The success of spinal fusion not only depends on accurate screw placement but also requires highly skilled technical expertise. It has been found that 4.2% of cases have shown neurovascular complications owing to misplaced screws (7). In addition, any error during the placement of a pedicle screw often results in injuries to the nearby blood vessels, nerves, and the spinal cord and may lead to paralysis.

The most commonly used method of pedicle screw fixation is free-hand placement; however, it depends on the technical expertise of the surgeon (8). It has been reported that the misplacement rates of pedicle screw ranges from 3% to 55% in the region of the thoracic spine (9). In comparison to fluoroscopy-assisted freehand screw placement approaches, robot-assisted pedicle screw insertion is a more successful surgical choice for osteoporosis patients who present with a variety of spine disease (10). On the other hand, radiographic imaging-based navigation techniques and computer applications contributed to the increased success rate of pedicle screw fixation and increases the accuracy of screw

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insertion by 87% (11). The navigation-based cervical pedicle screw placement approaches offer much higher accuracy and reduced complication rates (12).

One of the most commonly reported causes of pedicle screw failure is pull-out strength, which is the force necessary to pull the screw from the anchoring bone. The pull-out strength of the pedicle screw depends on various factors like length, outer diameter, and also its fitness within the bony canal of the pedicle, in the vertebral body (13). Even though a CT (Computed Tomography) scan can provide an accurate evaluation of the levels to be instrumented, the efficiency of CT scans is limited in estimating the true size of a pedicle (14). They also suggested that there is a need for a detailed understanding of the 3D-pedicle anatomy that may reduce surgical time.

Overall, it is clear that the accuracy of screw placement is critical to the success of spinal surgery, and also it is necessary to pre-plan the size and dimensions of pedicle screws specific for the vertebral column for successful pedicle screw fixation. Three-dimensional-printed (3DP) models are being utilized more frequently for surgical training and preoperative planning to increase the effectiveness of clinical learning (15). The breaches in the thoracic spine (2.5%) were more common than in the lumbar spine (0.9%) (16). To the author's knowledge, there are only limited papers available for determining pedicle screw diameter and length for the preplanning of thoracic pedicle screw fixation. Hence, in this study, we aim to investigate the optimum pedicle screw diameter and length in the region of T12 using CT images. By measuring correct pedicle screw length and diameter from preoperative or intraoperative CT scans in real-time, it is possible to customize implants (possibly reducing implant pull-out and failure), with increased placement accuracy, fewer neurovascular complications, and reduced plan time, and decreased cognitive load for the surgeon.

The pedicle screw fixation technique is a commonly used method owing to the ease of fixation along with its superior biomechanical advantage which provides them an edge over the other methods of spinal fixation (17-19). Nevertheless, anatomical variations often impose a great challenge, for accurate spinal fixation. It has been found that in 29% of cases pedicle wall violations have been reported even in the hands of the experienced surgeon (20). In addition, pedicle screw fixation in the region of the thoracic spine offers a great challenge to surgeons owing to its complex anatomy, and hence free-hand fixation technique becomes a daunting task. For example, in severe kyphoscoliosis, the pedicles are highly dysmorphic with distorted bony structures (21). Hence, a high level of technical expertise is needed for the free-hand spinal fixation method and often it is limited. This clearly illustrates the need for studies focusing on developing customized pedicle screw templates for accurate spinal fixation. Hence, in this study, we developed a technique to pre-plan pedicle screw template to reduce surgery time and protect nearby anatomical structures. Here, we employed a CT scan of human thoracic bone (T3-T12). Using Mimics software, the T12 region is segmented and the T12 pedicle diameter is found to be 7.50 mm (Figure.4a). The results of this study correlate with (22), in which the pedicle dimensions from T1 to L5 were measured in sixteen human cadaver spines. The results of this study indicate that pedicles at T12-L5 levels can accommodate screws ranging in the size 7 mm diameter. Similarly, Verma et al (23) the pedicle dimensions (T1 to T12 levels) were investigated on twenty dry vertebral columns and the mean pedicle diameter was found to be 7.89 ± 0.70 mm. Therefore, the pedicle screw diameter of our study is in-line with the findings of (24-27).

The lateral border of the superior facet can be used as a landmark for identifying entry point (28). According to Korkmaz and Özevren, the optimal pedicle screw length enables to a reduction in the possibility of injury in the region of the anterior cortex of the vertebral body and bleeding [29]. Hence, in this study, we determined the chord length of the pedicle screw in the region of T12. The chord length is defined as the distance between the posterior entry point of the screw and the anterior vertebral cortex. It is also referred to as the length of the pedicle at the mid-pedicle axis. In our study, the chord length of the pedicle screw is found to be 46.70 mm (Figure.4b). The results of our study correlate with the study by Korkmaz and Özevren, wherein the mean pedicle chord length was found to be 38.17 ± 2.54 mm and 36.62 ± 2.27 mm in male and female patients (29). Similarly, the results from our study are comparable to the chord length found by Muteti and ElBadawi (30) in an African population. In their study, the recommended length of the pedicle screw in the region of T12 was found to be 45mm. The increased chord length may be due to the longer stature of the African population.

METHODS

MIMICS (Materialise Interactive Medical Image Control Systems) software is used to extract bone data from the DICOM (Digital Imaging and Communication in Medicine) CT image and converted it to 3D thoracic vertebrae models. In addition, the pedicle screw is designed using AutoCAD (Automatic Computer-Aided Design). This is in turn followed by the analyses of the level of fit and lock of the developed pedicle screw onto the 3D lamina model in the MIMICS software. Finally, the template creation for pedicle screw trajectory is done with the help of 3-Matic software. The CT scan of male thoracic bone (T3-T12) with the following acquisition parameters: Pixel matrix 512, Pixel size 0.9375 mm, and slice thickness 1.25 mm. The flow chart representation of the screw trajectory template is shown in Figure. 1.

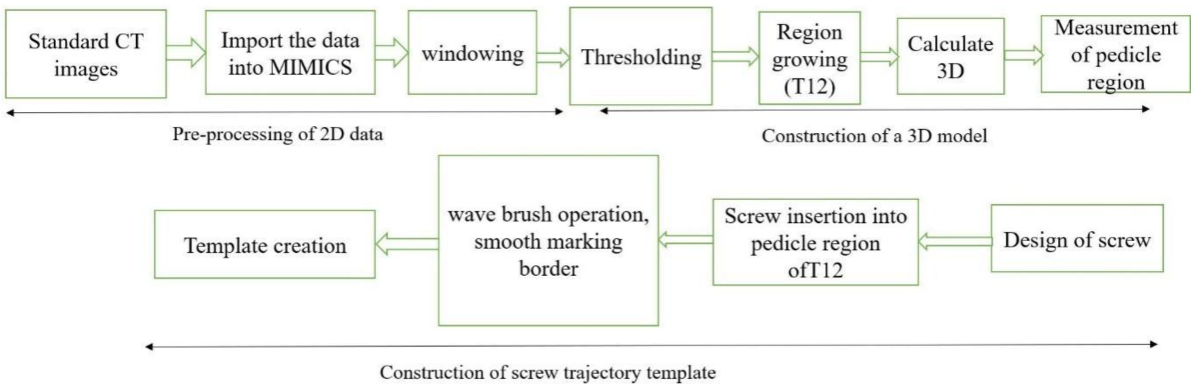

Figure.1 Block diagram representation of screw trajectory template.

The CT images are imported to the Materialize Mimics innovation suite as the first step. Next, the pre-processing of the images is performed by improvising the contrast by the windowing technique. The region of interest (thoracic region) that has been modelled is performed with the thresholding technique. In order to make a precise model, the region growing technique is applied which further segmented the T12 region. The optimal mode is selected to enhance the visualization quality of the developed 3D model using calculate 3D tool. Further pedicle region of T12 is measured for the design of the Pedicle screw. Later on, the designed screw is inserted into the pedicle region. Then, the region for the pedicle screw fixation template is marked and smoothed out using a wave brush and smooth marking border operation respectively. Finally, the computed assistive navigation template was created using a uniform offset operation.

RESULTS AND DISCUSSION

The CT images in DICOM format are imported to MIMICS software. The loaded images are represented in three consecutive planes axial (X-Y plane), sagittal (X-Z plane), and coronal (Y-Z plane) Fig. 2.

The T12 thoracic bone is segmented using the thresholding technique (226 – 3071 HU) from the loaded data. The segmented T12 region is represented in Figure. 2. The left, right, top, and isometric 3D anatomical representation of the segmented T12 region is shown in Figure. 3. From Figure. 4, the pedicle diameter and chord length for the thoracic screw fixation are found to be 7.50 mm and 46.70 mm.

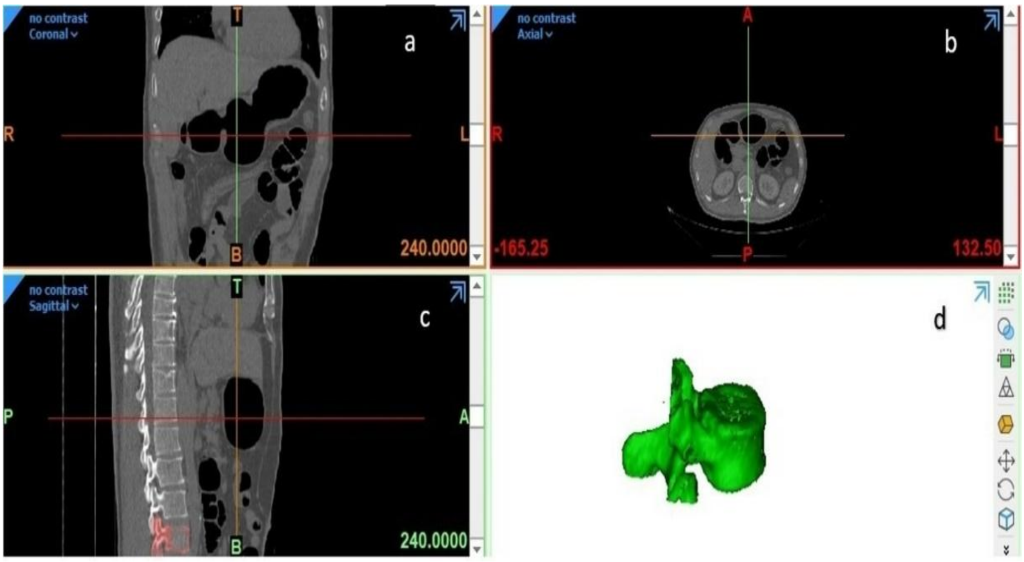

Figure. 2. (a) Coronal view; (b) Axial view; (c) Sagittal view; (d) Segmented T12 region.

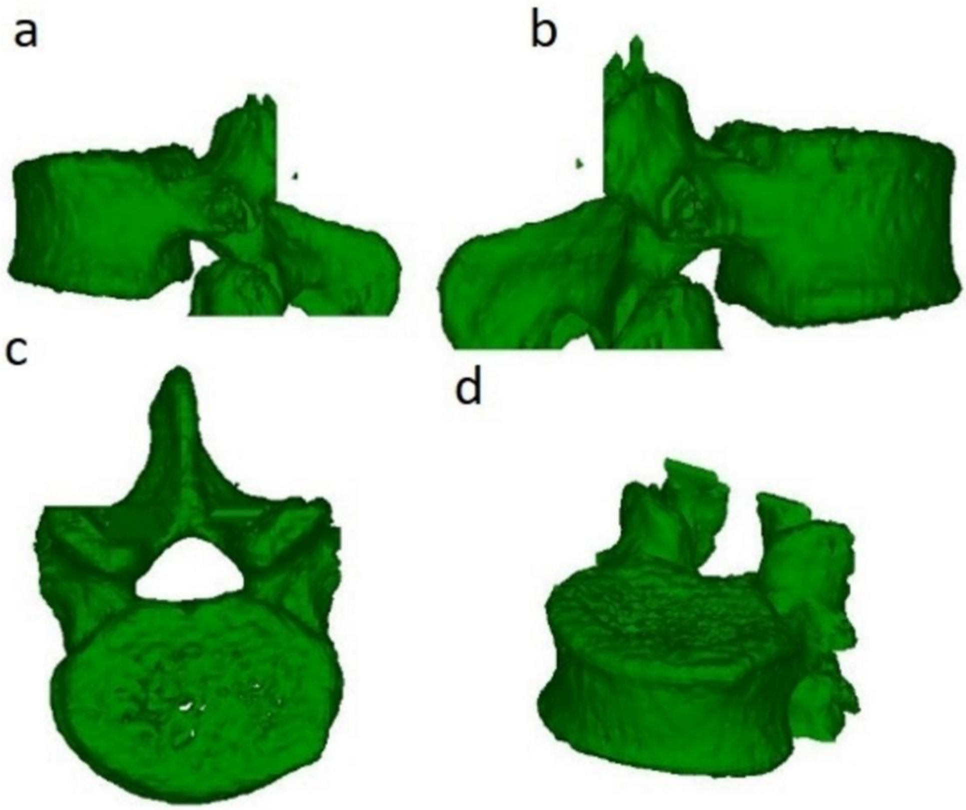

Figure.3 . (a) left view of 3D anatomical morphology of T12 vertebrae; (b) right view; (c) top view; (d) isometric view.

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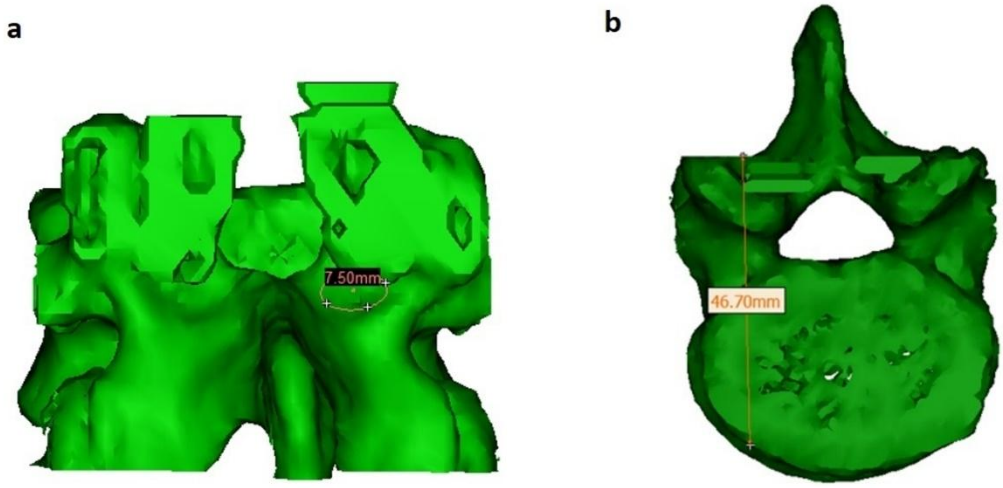

Figure. 4. (a)Posterior view of T12; (b) Top view of T12.

The customized pedicle screw for the above T12 vertebrae is developed using AutoCAD. The pedicle screw diameter and length of 7 mm and 38 mm are developed respectively using box and extrude tools in AutoCAD. The 2D and 3D view of the designed pedicle screw is shown in Figure. 5.

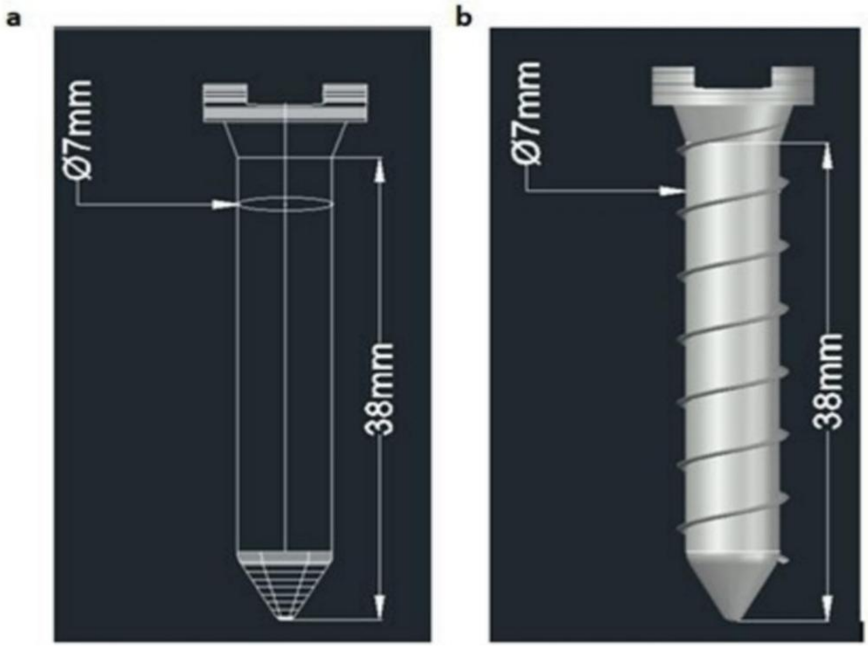

Figure. 5. (a) 2D view of pedicle screw; (b) 3D view of pedicle screw.

The simulated CAD model pedicle screw is then imported into MIMICS software and then the pedicle identification and trajectory planning are performed with the help of anatomic landmarks. The depth of pre-operative pedicle screw insertion is analysed and driven into the point of entry (lamina) of the T12 thoracic vertebrae, with the help of repositioning and replacing operations in MIMICS. The inserted screw in the thoracic vertebrae is shown in Figure. 6. The fitting of the pedicle screw into the lamina region is evaluated and simulation of screw insertion is assessed using transparency operation in MIMICS software. The distance between the lamina and the posterior part of the vertebral body is 46.70

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mm (Figure. 6) and the depth of pedicle screw insertion is 37.87 mm (Figure. 6) providing around 80% depth of insertion.

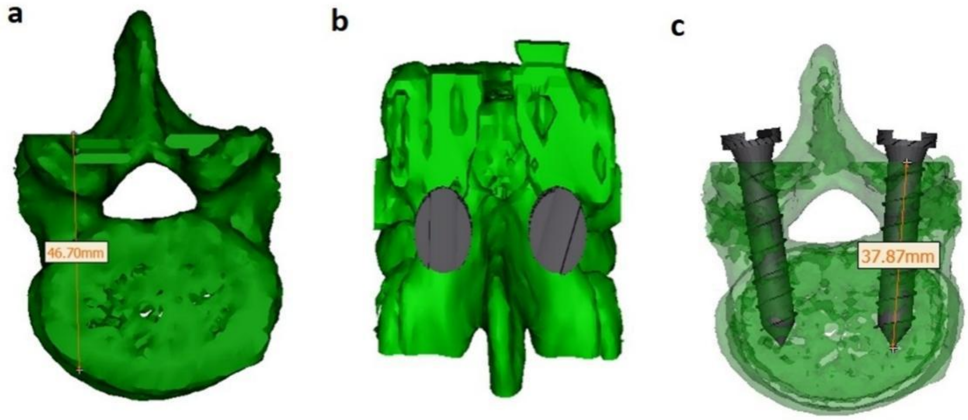

Figure. 6. (a) Top view of T12 vertebral body; (b) posterior view of pedicle screw insertion in T12; (c) pedicle screw fit into the lamina region

The screw navigation template is then developed by exporting the above 3D model to 3-Matic software. The 3-Matic software is used to mark the posterior surfaces near the pedicle screw for the further development of the template. All the marked boundaries are "smoothed," and the area is then propagated using the "uniform offset" function to create the navigation template's contact component (Figure. 7). The micropores near the pedicle region are merged using the “wrap” operation.

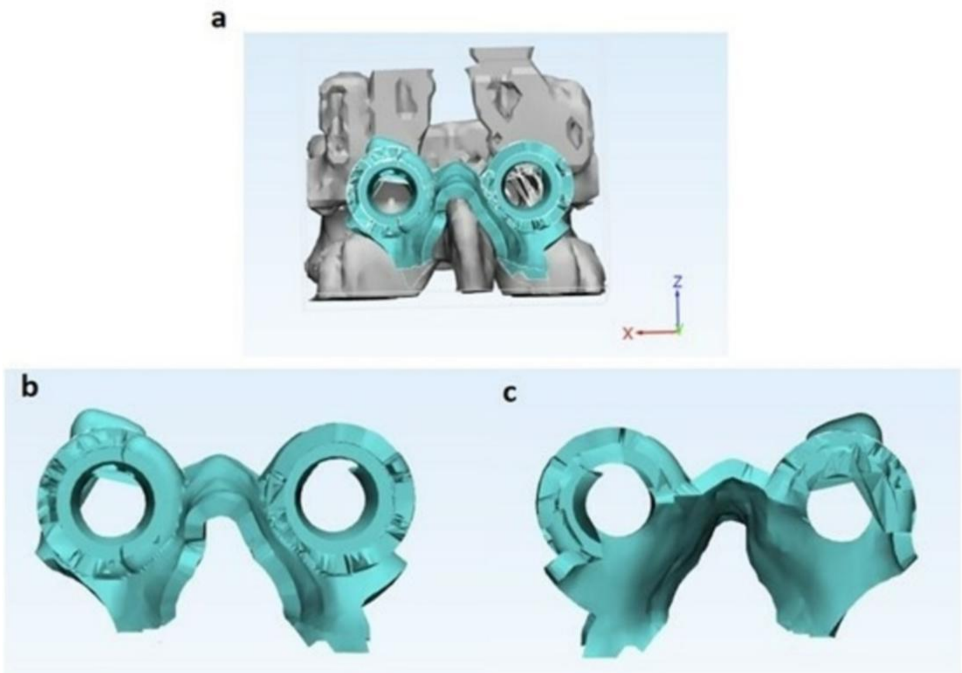

Figure. 7. (a) Screw trajectory templates locating screw entry points on the lamina; (b) Anterior view of the Screw Trajectory Template; (c) Posterior view of the Screw trajectory Template.

The recent advancements in 3D visualizing software have spurred growing opportunities in orthopedic surgery, especially the advanced navigation techniques that enable us to determine the optimal diameter and chord length of the pedicle screw. Thus, we can design customized pedicle screws

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according to the individual. Moreover, the developed trajectory template assists the surgeon in fixing the implant accurately, minimizing the risk of vertebral artery injury (VAI).

In a study by Defino and Vendrame (31), the pedicle was found to be a key determinant in offering the pull-out resistance in comparison to the vertebral body (60% versus 40%). Hence, the major parameter for screw pull-out resistance is the depth of pedicle screw insertion. In general, the safest screw pull-out resistance is found to be 80% pedicle screw insertion. According to Krag et al., the screw insertion should be 70-80 % of vertebral body length (32). This is in accordance with the results of our study, wherein the distance between the lamina and the anterior part of the vertebral body is 46.70 mm (Figure. 4) and the depth of pedicle screw insertion is 37.87 mm (Figure. 6) providing around 80% depth of insertion. In addition, Sugawara et al. suggested that the inappropriate fit of screw guide templates on the patient laminae often imposes a great challenge during spine surgery. Hence, they performed the 3D analysis of the screw template on the laminae (33). In the same way, we performed the fit and lock of the navigation template on the laminae using 3-Matic software and obtained favourable results (Figure. 7).

CONCLUSION

Inappropriate pedicle screw diameter and length may result in significant pull-out forces resulting in the fracture of neighbouring fragile bones. The key to effective spine fixation involves the accurate penetration of the pedicle screw along the pedicle axis, integrating the sagittal and transverse diameters. To the author’s knowledge, there were only limited studies dealing with the determination of pedicle screw diameter and chord length. Most of the available literature on pedicle screw diameter and chord length deals with real-time or direct measurement involving the free-hand spinal fixation method. However, this method imposes a greater risk owing to the highly dysmorphic nature of pedicles. This demands greater technical expertise and hence proper pre-planning is much more anticipated. Thus, there is a need for studies related to pre-planning orthopedic surgeries. Hence, this study provides a method to preoperatively determine pedicle screw diameter and chord length using 3D analysis of CT scans.

In this study, we designed a pedicle screw-based on the analysis of the affected pedicle in the region of T12. The developed pedicle screw, length, and depth of pedicle screw insertion were found to be 7 mm, 38 mm, and 37.87 mm, respectively. Finally, the 3D analysis of the screw template on the laminae is performed and was found to have a favourable fit and lock navigation template.

Thus, by determining pedicle screw length and diameter, it is possible to customize implants thereby reducing the risk of implant pull-out and failure. In addition, the proposed method offers accurate pedicle screw placement, fewer neurovascular complications, reduced surgical time, and decreased cognitive load for the surgeon. In this study, limited sample size and lack of clinical validation are the two major limitations. Hence, for future studies, clinical validation of the developed pedicle screw on larger sample size is planned for excessive spinal deformities like congenital scoliosis, atlantoaxial fixation, and hip surgery. Biomaterial analyses of the pedicle screw can be also done in the future.

In conclusion, the determination of pedicle screw length and diameter can be used to customize the pedicle screw surgical template. This method is a safe, cost-effective, and convenient method enabling accurate placement of pedicle screws in orthopedic surgeries and can be applied for a variety of spinal deformities.

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