Received: 2013.12.03
Accepted: 2014.01.31
Published: 2014.05.30

Finite element analysis of lumbosacral reconstruction after partial sacrectomy

Authors' Contribution:
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Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: The biomechanical property of MGT for patients who underwent partial sacrectomy is not well documented, so this study aimed to investigate biomechanical property of lumbosacral reconstruction after partial sacrectomy.

Material/Methods: Three 3-dimensional finite element models of lumbosacral region were established: 1) an intact model (INT), 2) a defective model in which partial sacrectomy was performed cephalad to S1 foramina (DEF), and 3) a re-constructed model (REC).

Results: Displacements of anchor point on L3 vertebrae in INT, DEF, and REC model were 6.63 mm, 10.62 mm, 4.29 mm (titanium), and 3.86mm (stainless steel), respectively. Stress distribution of the instrument in REC model showed excessive concentration on the caudal spinal rod, which may cause rod failure between spine and ilia. Maximum von Mises stress of the stainless steel instrument was higher than titanium instruments, and values of stress of the anchor point around the sacroiliac joint in the REC model were 26.4MPa with titanium instruments and 23.9 MPa with stainless steel instruments.

Conclusions: Lumbosacral reconstruction can significantly increase stiffness of the spinopelvis of patients who underwent partial sacrectomy. However, the rod between L5 and ilia is the weakest region of all instruments. Stainless steel instruments have higher risk of rod failure and are less suitable for lumboiliac arthrodesis than titanium instruments.

Keywords: **partial sacrectomy • reconstruction • biomechanics • finite element analysis**

Full-text PDF: <http://www.medscimonit.com/download/index/idArt/890134>

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Background

Partial sacrectomy is usually performed when a sacral tumor involves high-level sacral vertebra. Traditionally, surgical treatment without reconstruction often damaged the sacroiliac joint and the ligaments around it, and was often associated with prolonged immobilization during the recovery phase. Thus, lumbosacral reconstruction was often performed to achieve early ambulation for patients. Modified Galveston technique (MGT) is one of the most commonly used methods in lumbosacral reconstruction. The biomechanical property of MGT for patients who underwent partial sacrectomy is not well documented. In this study, a finite element analysis was carried out to evaluate the stiffness of MGT reconstruction and the stress of instruments in detail.

Material and Methods

Design

Three finite element models (FEMs) of the lumbosacral region were established: 1) an intact model (INT), 2) a defective model in which partial sacrectomy was performed cephalad to the S1 foramina (DEF), and 3) a reconstructed model (REC).

FEM of intact lumbosacral region (INT)

To create this model, computed tomography (CT) scans of L3-pelvis of a 53-year-old healthy man were obtained. The commercially available finite element program ABAQUS 6.7 (SIMULIA Inc., Providence, RI, USA) was used to model the lumbosacral region. The FEM of the intact lumbosacral region included L3–L5 vertebrae, intervertebral discs, endplates, posterior elements, sacrum, and the superior part of the bilateral ilia.

The material properties were assumed to be homogeneous and isotropic, and the data were adopted from the literature [1] (Table 1). A 10-node solid element (C3D10M) was used for modeling the cortical bone, cancellous bone, endplate, and disc. The facet joint was treated as a nonlinear 3-dimensional contact problem using surface-to-surface contact element, and the friction coefficient was set 0.1 [2]. To stimulate sacroiliac joint motion, spring elements were used to connect the joint faces of the sacroiliac joint. The spring stiffness was set as 200 N/mm according to validation in the literature [3]. The FEM of intact lumbosacral region (INT) consisted of 161 966 C3D10M elements, 160 spring elements, and 246 555 nodes (Figure 1A).

FEM of defective lumbosacral region (DEF)

The INT model was modified to simulate partial sacrectomy. Elements of sacrum caudal to the S1 foramina were deleted in

Table 1. Material properties used in FEM of lumbosacral region.

Material properties	Young's modulus (Mpa)	Poisson's ratio
Cortical bone	12,000	0.3
Cancellous bone	100	0.2
Posterior element	3,500	0.25
Cartilaginous endplate	4.2	0.45
Nucleus pulposus	1,667	0.48
Anulus fibrosus	4.2	0.45
Instrument (titanium)	110,000	0.3
Instrument (stainless steel)	210,000	0.3

ABAQUS CAE. The number of spring elements in the sacroiliac joint was also reduced to 120. The material properties (Table 1) and the stiffness of spring elements were the same as those in the INT model. The DEF model consisted of 147 927 C3D10M elements, 120 spring elements, and 225 450 nodes (Figure 1B).

FEM of reconstructed lumbosacral region (REC)

Instruments used in MGT reconstruction were mainly screws and rod. In this study, 6 pedicle screws (diameter 6.5 mm, length 45 mm) and 2 iliac screws (diameter 7 mm, length 45 mm) were inserted into the DEF model, and then connected by 2 rods (diameter 6 mm) and 2 cross-linkers (diameter 3 mm). The instrument morphology parameters were set according to commercially available products (ISOLA, Depuy, Inc.). In this study, the connection between screws and bone was assumed as firm, so the thread part of the screw was ignored. The instruments were also meshed with the C3D10M element. The material properties (Table 1) and the stiffness of spring elements were the same as those in the DEF model, and the material properties of instrument were considered as titanium or stainless steel. The REC model consisted of 216 403 C3D10M elements, 120 spring elements, and 260 677 nodes (Figure 1C).

Boundary and loading condition

A mean vertical load of 500N transmitted along the lower lumbar spine in upright standing position was identified in the literature [4]. Upright standing posture was simulated in these models. The inferior surfaces of the bilateral ilia were fixed completely, with a vertical load of 500 N imposed on the superior surfaces of the L3 vertebral body.

The middle point of superior endplate on the L3 vertebrae was taken as the anchor point to compare the displacement of the

Figure 1. Finite element models of intact lumbosacral region (INT, **A**), defective lumbosacral region (DEF, **B**), and reconstructed lumbosacral region (REC, **C**)

3 finite element models. The stress results are expressed in term of von Mises stresses, and stress distribution of instruments and sacroiliac joints in the REC model were evaluated.

Model validation

Under the same vertical load, the stiffness of INT and DEF model were compared with the data of Hugate et al. study [3]. In addition, the intact results served as baseline data for our interpretation of the results of other models.

Results

Displacement and stiffness of models

Displacement distributions of the 3 models are showed in Figure 2. The displacement of anchor point in INT, DEF, and REC models were 6.63 mm, 10.62 mm, 4.29 mm (titanium)

Figure 2. Displacement distributions of INT model (**A**), DEF model (**B**), and REC model (**C**). The material property of the instrument in this figure was titanium. Displacement results suggest that lumbosacral reconstruction can significantly increase the stiffness of the lumbosacral region in patients who underwent partial sacrectomy.

and 3.86 mm (stainless steel), respectively. Thus, the stiffness of the 3 models was 140 N/mm, 87 N/mm, 216 N/mm (titanium), and 240 N/mm (stainless steel). These results suggest that lumbosacral reconstruction can significantly increase the stiffness of the lumbosacral region of patients who underwent partial sacrectomy.

A good agreement between our stiffness results and reported data (INT 140 N/mm vs. 353 ± 231 N/mm reported; DEF 87 N/mm vs. 101 ± 49 N/mm reported) was confirmed, which validated our models.

Stress of instruments

Stress distribution of instruments in the REC model is shown in Figure 3. Excessive concentration on the caudal spinal rod could

Figure 3. Stress distribution of instrument in REC model. Excessive concentration on the caudal spinal rod could be observed, which may cause rod failure between spine and ilia. The maximum stress of stainless steel instruments was significantly higher than that of titanium instruments (992MPa vs. 655MPa).

be observed, which may cause rod failure between spine and ilia. The maximum stress of the stainless steel instrument was significantly higher than that of titanium instruments (992 MPa vs. 655 MPa). Meanwhile, 1-anchor points around sacroiliac joints in the REC model were selected. The value of stress of the anchor point was 26.4 MPa with titanium instruments and 23.9 MPa with stainless steel instruments. Our results strongly indicate that stainless steel instruments had higher maximum stress and greater stress shielding effect than titanium instruments.

Discussion

Partial sacrectomy is performed when a sacral tumor involves high-level sacral vertebra, which often breaks the sacroiliac joint and the ligaments around it. Traditionally, surgical treatment without reconstruction was often associated with prolonged immobilization during the recovery phase. Thus, lumbosacral reconstruction was usually performed to achieve early ambulation for patients. However, the biomechanical behavior of lumbosacral reconstruction for sacrectomy was not well documented. Since being first introduced by Gokaslan [5] in 1997 with development of flap surgery skills [6,7], MGT has become one of the most common methods in lumbosacral reconstruction for sacrectomy. In this study, we evaluated MGT reconstruction for partial sacrectomy using a finite element analysis, which is an effective procedure for biomechanically evaluating a reconstruction in detail.

The result of FEM should be interpreted as a trend only. The material properties are not exactly known for human tissues. Because of the variability of different human tissues, the FEM does not necessarily reflect the behavior of all specimens tested in the experimental part of the study. Thus, major differences may occur when compared with results of *in vitro* studies, as have been observed in previous studies [8,9]. The validation of finite element models is generally done through a comparison between the results yielded by models and experimental studies. Based on the results of the validation process as described, our FEMs have been sufficiently validated. However, the small numbers of specimens used in Hugate et al. study [3] limit the statistical power of the study and we cannot ensure the trends we report would occur clinically given the small numbers and the limited range of *in vivo* loading situations.

The mechanical consequences of partial sacrectomy and reconstruction are poorly understood. Destabilization of the spinopelvic segment may require bony stabilization and reconstruction using complex methods that involve lumboiliac arthrodesis. A

partial sacrectomy below the S2 foramina typically would not involve resection of the sacroiliac joints and would likely have little effect on stability [10,11]. Transverse osteotomy involving the S2 and S1 sacral bodies has been previously investigated by Gunterberg et al. [12], Hugate et al. [3], and Yu et al. [13]. It is believed that lumbosacral reconstruction should be performed for patients who underwent sacrectomy cephalic to the S1 foramina to achieve early ambulation.

Lumbosacral reconstruction can significantly increase the stiffness of the lumbosacral region of the patient who underwent partial sacrectomy. However, the rod between L5 and ilia is the weakest region of all the instruments, which is the same as the stress distribution in Zhu et al. study [1]. It is suggested that the bending of the rod should be conducted carefully and smoothly to avoid significant stress concentration and to reduce the risk of rod failure. Stainless steel has lower yield stress than titanium. In our study, stainless steel instruments reconstruction had higher maximum von Mises stress and significantly greater stress shielding effect than titanium instruments, which means stainless steel instruments have higher risk of rod failure and are less suitable for lumboiliac arthrodesis than titanium instruments.

We believe our findings contribute to better understanding of the mechanical consequences of lumbosacral reconstruction after partial sacrectomy. The FEM established in our study may be useful in designing better reconstruction instruments for lumbosacral reconstruction.

Conclusions

Lumbosacral reconstruction can significantly increase spinopelvic stiffness of patients who underwent partial sacrectomy. However, the rod between L5 and ilia is the weakest region of all the instruments. It is suggested that the bending of the rod should be conducted carefully and smoothly to avoid significant stress concentration and to reduce the risk of rod failure. Stainless steel instruments have higher maximum stress and significantly greater stress shielding effect than titanium instruments, which means stainless steel instruments have higher risk of rod failure and are less suitable for use in lumboiliac arthrodesis than titanium instruments.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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