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Biomechanical Evaluation of the Effect of MIS and COS Surgical Techniques on Patients with Spondylolisthesis using a Musculoskeletal Model

Sajad Azizi (PhD Candidate)[1], Mohammad Nikkhoo (PhD)[2,3]*, Mostafa Rostami (PhD)[4], Chih-Hsiu Cheng (PhD, PT)[2,3]

[1]Department of Biomedical Engineering, Faculty of Medical Sciences and Technologies, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]School of Physical Therapy and Graduate Institute of Rehabilitation Science, College of Medicine, Chang Gung University, Taoyuan, Taiwan
[3]Bone and Joint Research Center, Chang Gung Memorial Hospital, Linkou, Taiwan
[4]Department of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran

*Corresponding author: Mohammad Nikkhoo
School of Physical Therapy and Graduate Institute of Rehabilitation Science, College of Medicine, Chang Gung University, Taoyuan, Taiwan
E-mail: d000018523@cgu.edu.tw

Received: 24 June 2024
Accepted: 10 December 2024

ABSTRACT

Background: The biomechanical impacts of Conventional Open Surgery (COS) versus Minimally Invasive Surgery (MIS) fusion techniques on adjacent segments and their potential role in developing Adjacent Segment Disease (ASD) remain uncertain for spondylolisthesis.

Objective: This study aimed to investigate the impact of MIS and COS fusion surgeries on adjacent spinal segments for spondylolisthesis, through on muscle injury and developing ASD.

Material and Methods: This prospective and non-randomized controls study used a validated musculoskeletal model to compare the biomechanical effects of COS and MIS L_4/L_5 fusion surgery on patients with spondylolisthesis. The model incorporated kinematic data from 30 patients who underwent each surgery. A sitting task was simulated to model post-operative muscle atrophy, and the analysis focused on changes in biomechanics of adjacent spinal segments.

Results: Lumbar flexion was significantly greater (201%) in MIS vs. COS, despite similar pelvic tilt. Consequently, Lumbopelvic Rhythm (LPR) also increased in MIS (133%). Both techniques altered inter-segmental moments. While inter-joint load was higher in COS, only the lower joint's compressive load was significantly greater (67%). Additionally, MIS required lower overall muscle force with reduced loads and passive moment on spinal joints compared to COS.

Conclusion: This study demonstrates that MIS fusion preserves physiological LPR better than COS. MIS maintains normal spinal curvature and maintains lumbar lordosis. While open surgery can lead to abnormal curvature and increased muscle forces to compensate for spinal stability. The study emphasizes the importance of paraspinal muscles in influencing spinal load distribution during MIS compare to COS.

Keywords

Spondylolisthesis; Spine; Minimally Invasive Surgical Procedures (MIS-P); Conventional Open Surgery (COS); Musculoskeletal Models (MS)

Introduction

Spine fusion is a common surgical intervention for spinal disorders. However, a frequent complication is adjacent segment degeneration (ASD) [1, 2]. The exact pathogenesis of ASD remains unclear, with varying perspectives on the matter. Some studies suggest that it is a natural consequence of aging [3-5], while others attribute it to an accelerated degenerative process resulting from the altered biomechanics of the fused spine [6-9]. In line with this, studies have shown that increased disc loading accelerates disc degeneration [10-12].

Open fusion surgeries induce substantial structural modifications to the spine, which can consequently alter the load distribution across adjacent vertebral levels. These surgical procedures often necessitate the detachment of paraspinal muscles from the posterior spinal elements to provide adequate exposure for laminectomy/facetectomy or bone graft placement [13]. Moreover, lateral retraction of the paraspinal musculature to maintain an adequate surgical field can inadvertently result in iatrogenic injury to these muscles [14-16]. Such injuries may consequently alter the biomechanical loading of the spine, particularly at adjacent spinal levels, and may play a contributing role in the pathogenesis of adjacent segment degeneration. To mitigate adverse effects, minimally invasive surgeries and flexible instrumentation are being developed as alternatives to open fusion [17]. The impact of these techniques on spinal biomechanics and their efficacy in preventing adjacent segment degeneration is not fully understood. Given the limited understanding of how surgical muscle injury influences spinal loading, additional studies are warranted to elucidate this relationship and develop strategies to mitigate the risk of adjacent segment degeneration.

Comparative studies have indicated that minimally invasive spine surgeries may be associated with a reduced risk of developing asymptomatic adjacent segment disc disease, potentially due to less tissue disruption and altered biomechanics compared to traditional open techniques. In a study of 304 patients who underwent Minimally Invasive Transforaminal Lumbar Interbody Fusion (MI-TLIF), the reoperation rate for ASD was only 2% [18]. Similarly, two other retrospective studies reported ASD rates following minimally invasive single-level fusion with Posterior Pedicle Screw Fixation (PPSF) of 9.5% and 8.7% at 5 and 3 years, respectively, and symptomatic ASD rates were lower at 3.2% and 1.9% [18, 19]. While some studies have found no significant difference in the incidence of symptomatic adjacent segment degeneration between open and minimally invasive TLIF [20-22], the relative efficacy of these approaches in preventing this complication and the underlying biomechanical mechanisms remain unclear. Therefore, to gain a more comprehensive understanding, high-detail musculoskeletal modeling studies are needed to quantify spinal loads and assess the impact of different surgical techniques on adjacent segment degeneration.

A study by Min et al. [23] compared the prevalence of radiographic ASD in 48 patients undergoing Anterior Lumbar Interbody Fusion (ALIF) and Posterior Lumbar Interbody Fusion (PLIF) for spondylosis. The study found a significantly higher the prevalence of ASD in the PLIF group. These findings suggest that preservation of posterior muscles in ALIF may play an important role in reducing radiographic ASD. Therefore, the utilization of high-fidelity musculoskeletal models represents a suitable methodology for assessing the influence of surgical muscle damage on the development of adjacent segment degeneration when evaluating different surgical techniques. Additionally, several studies have assessed the degree of surgical muscle damage, quantified by reductions in muscle Cross-Sectional Area (CSA) or the removal of muscle fascicles within the fusion zone, as a key differentiating factor among various fusion techniques. For example, Bresnahan [24] and Kumaran [25] employed musculoskeletal models to examine the impact of reduced muscle CSA on muscle activation patterns, forces, and subsequent intervertebral disc stress and pressure. However, Bresnahan did not assess the effects of CSA reduction on spinal axial loading and other biomechanical parameters. Moreover, Kumaran's model assumed a constant range of motion across all levels of muscle damage, which is not representative of real-world conditions, as the severity of muscle damage can significantly affect spinal flexibility.

To differentiate the effects of iatrogenic muscle injury caused by various surgical techniques, Malakoutian [26] and Rasmussen [27] modeled the removal of muscle fascicles within the fusion area. Malakoutian employed a forward dynamics-assisted data tracking approach to analyze kinematics, whereas Rasmussen utilized kinematic data from healthy subjects as a baseline for all surgical techniques. Despite the well-established link between movement kinematics and spinal loading, previous research has been limited by the lack of real-world in vivo data comparing MIS and COS surgical techniques. While alterations in lumbar spine rhythm have been shown to significantly affect spinal loads [28-30]. This study is the first to employ a high-detail MS model to investigate the effects of surgical muscle injury on spinal loading at adjacent levels using actual in vivo data from both MIS and COS surgical groups.

Material and Methods

Participants and Surgical Protocols

This prospective and non-randomized controlled study protocol was approved by the Institutional Review Board of Chang Gung Memorial Hospital and the Clinical Research Committee of the Faculty of Medical Sciences and Technologies, Science and Research Branch, Islamic Azad University. A prospective study was conducted to compare the biomechanical outcomes of minimally invasive surgery and conventional open surgery in patients with single-level L_4/L_5 spondylolisthesis presenting with low back pain and radiculopathy. The study adhered to STROBE guidelines (Strengthening the reporting of observational studies in epidemiology) [31, 32]. Thirty-one patients participated in the study. Fifteen patients underwent conventional open surgery (COS, mean age 58.32±7.6 years, Body Mass Index (BMI) 25.6±3.4, and 16 patients underwent minimally invasive surgery (MIS, mean age 60.32±9.8 years, BMI 25.2±2.8). All participants provided written informed consent prior to enrollment. Inclusion criteria were single-level spondylolisthesis (L_4/L_5 level), segmental instability, and disc degeneration disease with herniation and/or spinal stenosis. Exclusion criteria included previous spinal surgery, trauma, infection, psychiatric disorders, malignancies, BMI greater than 40 kg/m², age under 18 years, pregnancy, allergies to nickel or titanium, and chronic neurological or musculoskeletal diseases affecting balance. The COS group underwent a free-hand midline approach, preserving the supra- and interspinous ligaments for enhanced spinal stability. Laminectomy at the fusion level (e.g., L_4/L_5 decompression for L_4/L_5 fusion) aimed to relieve nerve compression. Conversely, the MIS group employed fluoroscopy-assisted percutaneous instrumentation through a para-median approach. Expandable retractors facilitated unilateral laminotomy and medial facetectomy for targeted decompression, minimizing disruption to the posterior musculature. All patients received Transforaminal Lumbar Interbody Fusion (TLIF) with a cage and transpedicular screws for spinal stabilization. However, the COS group received additional unilateral or bilateral PosteroLateral Fusion (PLF) based on available autogenous bone graft volume, potentially enhancing rigidity. The MIS group received only TLIF. All participants wore a Taylor brace for 3 months post-operatively.

Functional tests assessed paraspinal muscle activity: visual analog scale (VAS, 0-10), Oswestry Disability Index (ODI%), and Japanese Orthopedic Association (JOA) score questionnaires. All patients were evaluated at the

3-month follow-up (Table 1).

Experimental Methods and Data Analysis

Participants performed a standardized stand-to-sit task as quickly as possible for both MIS and COS fusion techniques. Seat height was individually adjusted to achieve 90 degrees of hip and knee flexion during full knee extension. With their arms crossed over their chests throughout the task, participants were instructed to stand up fully and then sit down completely. Kinematic data were collected using 6 Xsens MTw Awinda IMUs (Xsens, Enschede, The Netherlands) at a sampling frequency of 50 Hz. Inertial Measurement Units (IMU) placement was on the mid-lateral aspect of the lower leg and thigh, pelvis (midline of the spine at L_5/S_1), and lumbar (midline of the spine at T_{12}/L_1) [33]. A Butterworth zero phase low pass filter with a cut-off frequency of 6 Hz was used to remove noise. Ground Reaction Force (GRF) and moment data were measured during the task using a force plate (Kistler 9260AA6, Kistler Instrumented AG, Winterthur, Switzerland) at a sampling frequency of 1000 Hz.

Table 1: Clinical Outcomes between Two Surgical Procedures (Oswestry Disability Index (COS) and Minimally Invasive Surgery (MIS)) at three months post-surgery.

Parameter	COS	MIS
	Post-op	Post-op
JOA	63.6 (7.4)	65.3 (6.5)
ODI (%)	10.5 (11.8)	14.6 (15.3)
VAS (0-10)		
Back	1.2 (1.8)	0.9 (1.8)
Leg	0.5 (1.3)	0.7 (1.2)
Pain Level		
Lower Back Pain	1.2 (1.8)	0.9 (1.8)
Hip & Leg Pain	0.5 (1.2)	0.8 (1.3)
Hip & Leg Numbness	0.8 (2)	1.2 (1.9)
Operation Data		
Blood Lose (ml)	392.9 (235)	216.7 (38)
Surgical time (min)	107 (35)	242.7 (131)

JOA: Japanese Orthopedic Association; ODI: Oswestry Disability Index; VAS: Visual Analog Scale; COS: Conventional Open Surgery; MIS: Minimally Invasive Surgery; op: Operation

A. Modeling and Modification of the Musculoskeletal System

A validated musculoskeletal OpenSim model (version 3.3) with a detailed lumbar spine was employed to estimate back muscle forces and joint loads during MIS and COS techniques [34]. A 30-segment musculoskeletal model was developed, including 29 degrees of freedom and 238 Hill-type muscle fascicles to represen trunk musculature (Figure 1). The trunk was segmented into eight rigid bodies (fused pelvis-sacrum, L_5/L_1 vertebrae, and upper body) connected by six spherical joints at each intervertebral level (T_{12}/L_1 to L_5/S_1). Linear kinematic constraints were applied to distribute total lumbar spine motion across these joints according to established literature ratios for flexion/extension [35], lateral bending [29], and axial rotation [30].

B. Kinematics Constraint's

To assess the kinematic changes caused by fusion surgery in each lumbar joint using both COS and MIS techniques, coefficients derived were employed from established research. The range of motion for each lumbar joint (L_1/L_2 to L_5/S_1) was determined as a percentage of the total Range of Motion (ROM) for the entire lumbar region, based on in vivo data [36, 37]. The degenerated model, representing the pre-surgical state, exhibits a 20% reduction in the LPR value. Additionally, lumbar rotations adapt to compensate for the diminished motion at the L_4/L_5 segment. This compensation manifests as increased angular motion at the T_{12}/L_1 and L_5/L_1 levels. Consequently, the total lumbar rotation decreases significantly, dropping from 21.5% in the healthy model

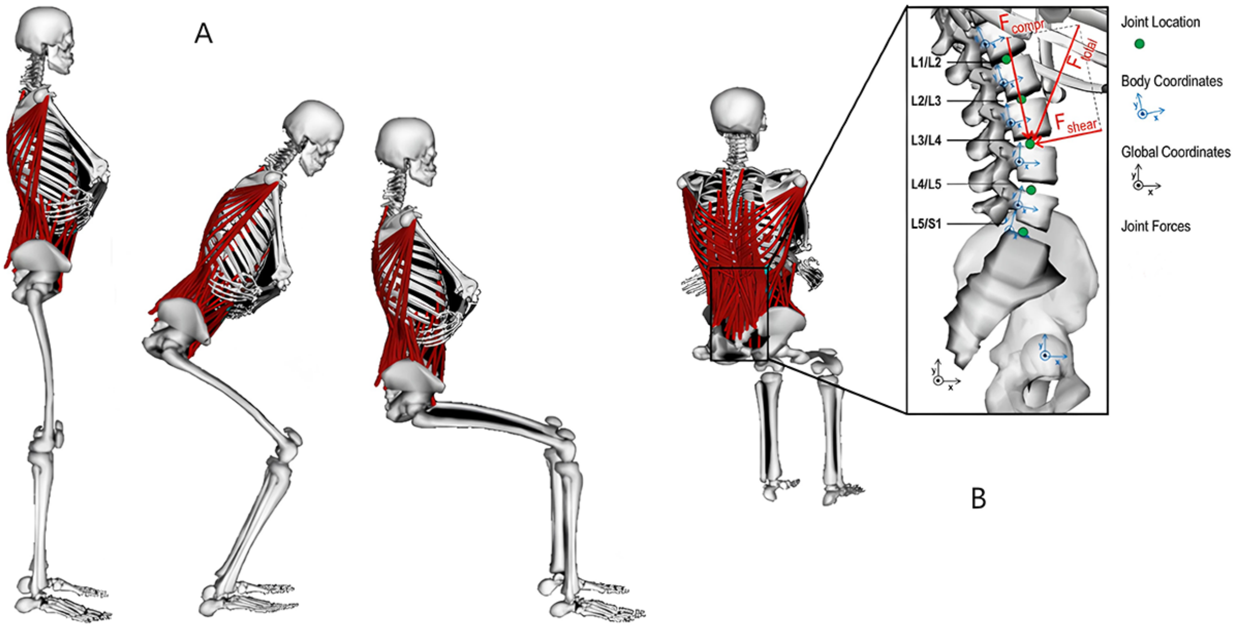

Figure 1: A: Full-body musculoskeletal model with 238 muscle-tendon actuators for the trunk during the Stand-to-Sit position. **B:** Musculoskeletal model of the trunk with a detailed view of the lumbar spine. The global body coordinate system is shown in black, the locations of the lumbar vertebral facets are indicated by green dots, and the local coordinate system for each lumbar vertebra is shown in blue. Intervertebral joint reaction forces are shown in red within their respective local coordinate systems. Thus, a positive x-component represents anterior-posterior shear force, and a positive y-component represents compressive force, as illustrated for the L_3/L_4 intervertebral joint.

to only 8% in the degenerated model. The distribution of rotational contributions across the lumbar spine is altered in the degenerated model. While the healthy model demonstrates contributions of 11.5% and 15% from the T_{12}/L_1 and L_5/S_1 segments, respectively, these contributions increase to 19.5% and 18% in the degenerated model. The total range of motion was distributed as follows: 3% for L_1/L_2, 19% for L_2/L_3, 38% for L_3/L_4, and 40% for L_5/S_1. Note that the L_4/L_5 segment had no motion due to fusion. Following kinematic calculations, these constraints were deactivated during dynamic analysis. Kinematic constraints introduce artificial moments that do not exist in real joints, and their deactivation ensures a more realistic representation of joint behavior. Furthermore, to enhance model accuracy, custom intercostal-sternal joints were replaced with rigid WELD joints, thereby eliminating unnecessary rotational degrees of freedom. Additionally, in the fused state, the L_4/L_5 joint was converted to a WELD joint to accurately reflect the post-surgical loss of motion.

C. Postoperative Muscle Changes

A comprehensive musculoskeletal model was utilized in this study, with a detailed representation of the upper limb musculature, including 238 upper-limb tendon-muscle actuators [34]. However, to reduce computational complexity, the lower limb musculature was simplified, using ideal moment actuators to control joint movements (Figure 1).

The model segmented the torso musculature into eight primary groups, including back muscles, further categorized as local muscles (ICPL: Iliocostalis Lumborum Pars Lumborum, LGPL: Longissimus thoracis Pars Lumborum, LTPL: Latissimus dorsi Part Lumborum, MF: Multifidus; QL: Quadratus Lumborum) and global muscles (ICPT: Iliocostalis Lumborum Pars Thoracis, LGPT: Longissimus thoracis Pars Thoracis, LTPT: Latissimus dorsi Part Thoracis). The optimization analysis revealed that the antagonist abdominal muscles (IO: Internal Oblique; EO: External Oblique; RA: Rectus Abdominis) were inactive during the analyzed motion. Importantly, all muscle properties remained consistent with the established Beaucage-Gauvreau model [38].

A critical differentiating factor between MIS and COS techniques for spinal fusion lies in the extent of iatrogenic muscle damage and subsequent reduction in muscular strength. This disparity arises from the differing degrees of paraspinal muscle detachment necessitated by the surgical approaches. COS procedures typically require more extensive surgical exposure, resulting in the severance of muscle attachments to the spinous processes, superior articular processes, and laminae. This greater degree of muscle disruption inherently results in more significant muscle damage compared to MIS techniques. Furthermore, previous studies [18, 39-41] have consistently demonstrated that sustained retractor pressure during surgery can cause significant ischemic injury to the paraspinal musculature, resulting in post-operative atrophy and impaired muscle function.

The multifidus, longissimus, and iliocostalis, comprising the primary paraspinal musculature [18, 42], are highly susceptible to iatrogenic injury given their intimate attachments to the vertebral column. To model the effects of paraspinal muscle damage at the fused L_4-L_5 level, as commonly observed in the COS technique, the model simulated complete detachment of the three target paraspinal muscles from their bony attachments. This reflects the potential for muscle detachment during open surgery. Conversely, the MIS technique assumed no muscle removal, consistent with the minimal tissue disruption associated with this approach. For fascicles with bilateral attachments, if at least one point resided at the damaged level (L_4/L_5), the entire fascicle was removed from the model. However, for fascicles with multiple attachments, a more nuanced approach was used. Only the connections at the fused level were eliminated, while the remaining attachments were maintained in the model.

Data Processing and Analysis

This study utilized subject-specific musculoskeletal models to investigate the biomechanical effects of spinal fusion techniques. A generic musculoskeletal model was scaled to each patient's anthropometry in both the COS and MIS groups. This scaling ensured accurate weight distribution within the model. Additionally, muscle properties, such as optimal fiber length, tendon slack length, and muscle moment arms, were also scaled using the same algorithm.

An Inverse Kinematics (IK) tool was used to calculate spinal joint angles for each surgical technique, accounting for the specific kinematic constraints imposed by both COS and MIS fusion procedures. Subsequent analyses were performed using OpenSim software. The Inverse Dynamic (ID) tool calculated the external forces and moments acting on the lumbar spine during movement. Additionally, Static Optimization (SO) analysis was performed to estimate muscle forces required to maintain the desired posture. The optimization algorithm minimizes a cost function that represents the minimal force required by muscles to satisfy the equilibrium equations. Finally, Joint Reaction (JR) analysis was used to quantify the loads acting on the intervertebral joints adjacent to the fusion site.

Given the model's assumption of sagittal plane symmetry, lateral shear forces were considered negligible. Therefore, the analysis primarily focused on anterior-posterior shear forces and axial compression within the local coordinate system of each vertebral segment. These forces were assessed at the fusion-adjacent levels (L_3/L_4 and L_5/S_1) during the moment of maximum lumbar flexion within a Sit-to-Stand motion.

Statistical Tests

Data normality was assessed using the Shapiro-Wilk test. For variables that were normally distributed and had equal variances, a two-sample independent t-test was employed to compare the mean values between the MIS and COS groups. When the assumption of equal variances was violated, Welch's t-test was used. For non-normally distributed variables, the non-parametric Mann-Whitney U test was employed for comparisons between MIS and COS groups.

Paired-sample t-tests were used to compare upper and lower joints within both the MIS and COS groups for variables that were normally distributed. For variables that did not meet the normality assumption, Wilcoxon signed-rank tests were employed. All analyses were performed using SPSS v27.0 (SPSS, Inc., Chicago, IL, USA) with a significance level of P-value<0.05.

Results

Kinematic Variation of the Lumbopelvic between COS and MIS

Figure 2 illustrates the kinematic changes of the pelvic and lumbar joints in both MIS and COS techniques. No significant differences in pelvic tilt were observed between two groups across all planes of motion. Although mean values for pelvic tilt and rotation were slightly lower in the MIS group, these differences were not statistically significant. Notably, pelvic list was approximately 3.03 times greater in the MIS group compared to the COS group, but this difference was also not statistically significant. Despite the similar trend in pelvic kinematics between MIS and COS, lumbar flexion was significantly and remarkably higher in the MIS group compared to the COS group (P-value=0.002), which was 2.01 times higher. Given the negligible changes in pelvic tilt between MIS and COS and the significant increase in lumbar flexion,

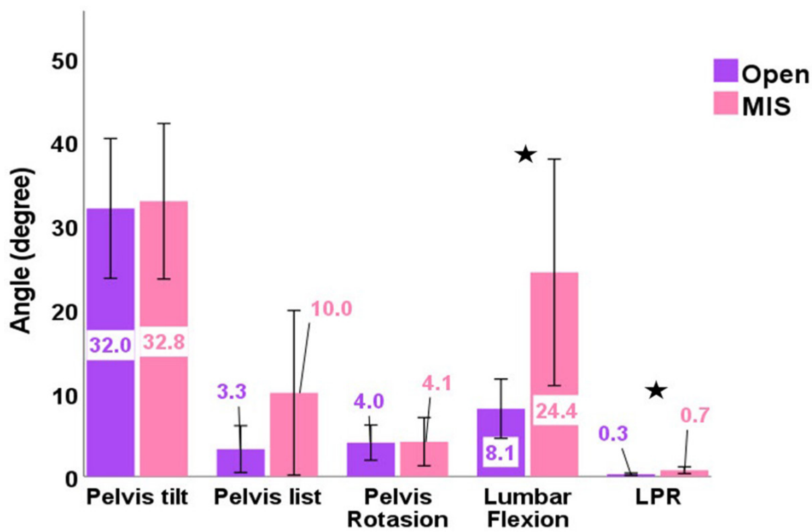

Figure 2: Mean values of Pelvic Tilt, List, and Rotation Angles along with Lumbar Flexion Angle in Degrees and Lumbopelvic Rhythm (LPR) between Minimal Invasive Surgery (MIS) and Conventional Open Surgery (COS) fusion techniques. *: Significant level

the changes in LPR were also significantly different between the two surgical techniques (*P*-value=0.007), with a 1.33-fold increase in LPR in the MIS group compared to the COS group. While pelvic tilt angles were similar between the MIS and COS groups, lumbar flexion was significantly reduced in patients undergoing COS compared to those undergoing MIS. These findings indicate that the MIS technique maintained a more physiologic lumbar lordosis compared to traditional open surgery.

Kinematic and Kinetic Changes of Adjacent Segments in Spinal Fusion: A Comparison between MIS and COS Techniques

In our previous analysis, we demonstrated that lumbar flexion was significantly greater in the MIS technique compared to COS. Figure 3 further illustrates these differences in trunk flexion angle for each surgical group, categorized by the levels adjacent to the fusion. The results consistently showed that flexion angles were significantly higher in MIS compared to COS for both the upper and lower levels of the fusion site. For MIS, the flexion angle increased by 1.86-fold (*P*-value=0.003) and 1.79-fold (*P*-value=0.001) in the upper and lower levels, respectively. Additionally, the flexion angle at the L_5/S_1 joint was marginally higher than at L_3/L_4 in both MIS and COS groups, but this difference was not statistically significant (*P*-value=0.981). Figure 3 shows that the external moment was generally higher in MIS compared to COS at both the upper and lower fusion levels, although this difference was not significant (*P*-value=0.081). However, for both surgical techniques, the external moment increased significantly from the upper to the lower level (*P*-value=0.011). Specifically, in COS, the external moment at L_5/S_1 was 28% greater than at L_3/L_4, while in MIS, it was 27% greater (*P*-value<0.001).

Similar to the external moment, no significant difference was observed in the mean passive moment between MIS and COS techniques at any of the joints adjacent to the fusion site (*P*-value>0.634). Passive moment in MIS increased by approximately 6% at the L_5/S_1 level and decreased by 6% at the L_3/L_4 level compared to COS. However, the results showed a significant difference in passive moment between the upper and lower levels within each surgical technique (*P*-value<0.001). In both COS and MIS, the passive moment at the L_3/L_4 level was substantially lower, by 75% and 78%, respectively, compared to the L_5/S_1 level.

Figure 3 illustrates the trend of compressive and shear load changes between the MIS and COS surgical techniques separately at the adjacent levels to the fusion site. The results revealed that the compressive load was significantly different between MIS and COS only at the L_3/L_4 level (*P*-value=0.045), with the mean compressive load in MIS being 2.4-fold higher than that in COS. Conversely, the anterior-posterior shear force showed significant differences between MIS and COS at both L_3/L_4 and L_5/S_1 levels. Specifically, the anterior-posterior shear force in MIS significantly increased by 146% (*P*-value<0.001) and 243% (*P*-value=0.008) compared to COS at the upper and lower joints, respectively. Notably, no significant differences in compressive and shear force values were observed between the two adjacent levels to the fusion site within either MIS or COS groups.

Figure 4 illustrates normalized values of inter-joint shear and compressive forces, as well as passive and resultant moments at the joints adjacent to the fusion site. Although Figure 2 did not show significant differences in external and passive moments between the MIS and COS methods at either adjacent level, normalized values of passive and external moments were significantly different between MIS and COS methods at both adjacent levels. Minimally invasive surgery significantly reduced external and passive moments at levels adjacent to the fusion site during

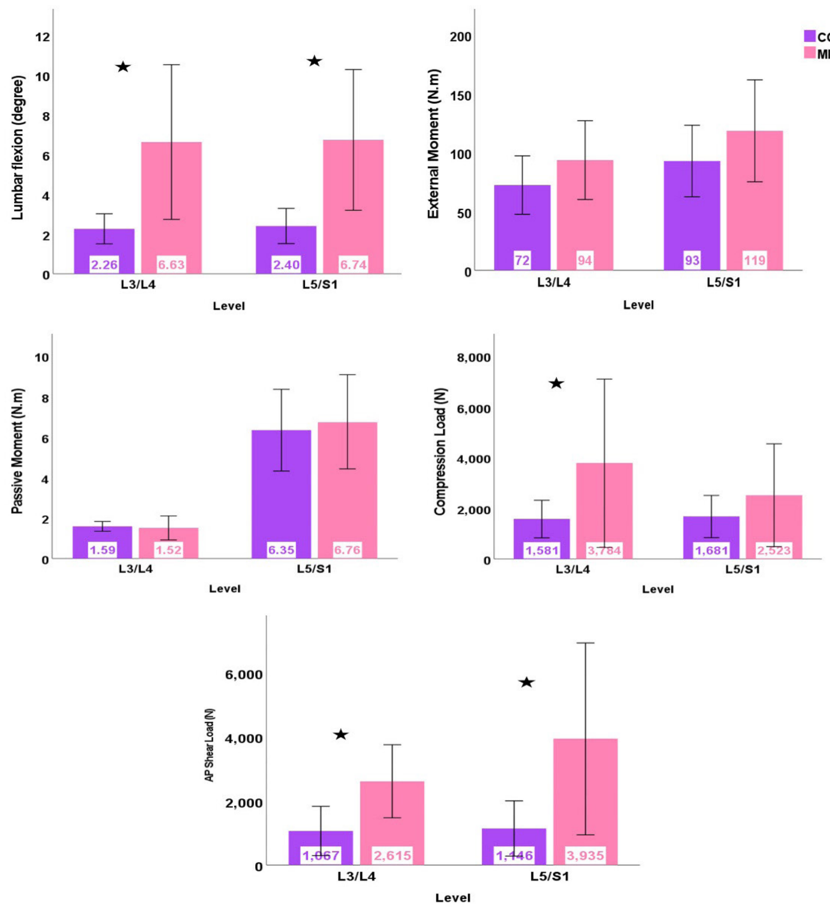

Figure 3: Mean values of flexion angle (degrees), external moment (N.m), passive moment (N.m), compressive force (N), and anterior-posterior shear force (N) at each adjacent segment of fusion joint (L_3/L_4, L_5/S_1) between Minimal Invasive Surgery (MIS) and Conventional Open Surgery (COS) fusion techniques. AP: Anterior-posterior, *: Significant level

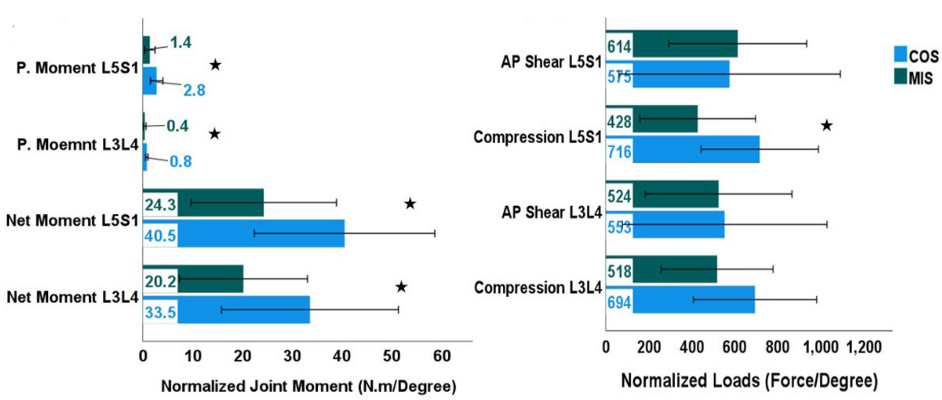

Figure 4: Normalized values of compressive and shear loads, passive moment (P. Moment), and total external moment (Net Moment) at the upper (L_3/L_4) and lower (L_5/S_1) fusion site joints between the Minimal Invasive Surgery (MIS) and Conventional Open Surgery (COS) fusion techniques. *: Significant level

maximal trunk flexion compared to conventional open surgery (*P*-value<0.006 and *P*-value<0.001, respectively). Figure 4 also showed that the significant differences in normalized shear and compressive forces between the MIS and COS surgical methods were opposite to the non-normalized state. In the normalized condition, inter-joint forces at the levels adjacent to the fusion site demonstrated a significant increase in compressive force only at the inferior level in the COS method compared to the MIS method (*P*-value=0.024). No significant difference was found in the normalized compressive force at the superior level (*P*-value=0.065). Normalized shear force did not show significant differences between the MIS and COS methods at either level (*P*-value<0.868).

Muscle Force Changes in Lumbar and Thoracic Regions between MIS and COS Techniques

Figure 5 illustrates the changes in lumbar and thoracic muscle forces during MIS and COS surgical methods. The results indicated that the mean muscle force across all three sections of the MF muscle was considerably higher in MIS compared to COS, but these changes were only significant for the spinous section. The force generated by the Multifidus-Spinous Part (MF-SP) was 2.05 times greater in MIS compared to COS (*P*-value<0.001). However, no significant differences were found in the force generated by the laminar and transverse part of the multifidus muscle (*P*-value>0.055). While the lumbar region of the iliocostalis lumborum muscle showed no significant change, the thoracic portion exhibited a significant 43% increase in force following MIS compared to COS (*P*-value=0.037). Notably, both the lumbar and thoracic regions of the Longissimus (LG) muscle demonstrated significant increases of 38% (*P*-value=0.013) and 39% (*P*-value=0.007), respectively, in MIS group compared to the COS group. The Quadratus Lumborum (QL) muscle did not

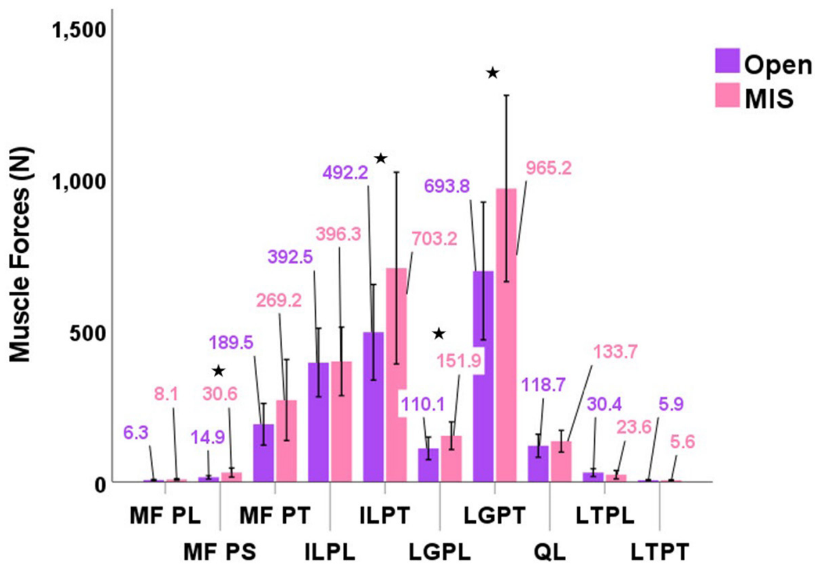

Figure 5: The average muscle forces of the Multifidus (MF) in its three compartments (laminar (MF-LP), spinous (MF-SP), and transverse (MF-TP)), the lumbar portion of the Iliocostalis (ILPL) a thoracic portion (ILPT), the lumbar portion of the Longissimus (LGPL) and thoracic portion (LGPT), the Quadratus Lumborum (QL), the lumbar portion of the Latissimus dorsi (LTPL), and the thoracic portion (LTPT) in both Minimal Invasive Surgery (MIS) and Conventional Open Surgery (COS) fusion techniques. *: Significant level

show any significant differences between MIS and COS (*P*-value=0.289). Although the Latissimus dorsi (LT) muscle force was reduced in both lumbar and thoracic regions after MIS relative COS. This decrease was not statistically significant (*P*-value>0.187).

Normalized back muscle force variations between MIS and COS methods at maximum flexion angle during a stand-to-sit task revealed distinct results compared to non-normalized conditions (Figure 6). In the normalized state, lumbar muscle forces were significantly higher in the COS method compared to the MIS method across almost all muscles (*P*-value<0.007). However, no significant differences were observed in the MF muscle's spinous portion (*P*=0.225). Excluding the MF-PS muscle, lumbar muscle forces in the COS method were approximately twice those of the MIS method. Normalized forces in the thoracic region were generally higher than in the lumbar region.

Results indicated that during maximum trunk flexion in the seated task, the IL muscles exerted greater force in the lumbar region compared to the MF-PL and LG muscles in both the MIS and COS methods. Conversely, normalized forces in the LT, MF-PT, and MF-PS muscles were negligible in this lumbar posture.

Discussion

In this study, we evaluated the biomechanical effect of iatrogenic muscle injuries in fusion surgery between COS and less invasive MIS methods with in vivo data using a high-detail musculoskeletal model in a daily high ROM task (stand-to-sit). Previous studies have not investigated the impact of muscle injuries during fusion surgery on patient-specific biomechanical factors contributing to adjacent segment disease across various

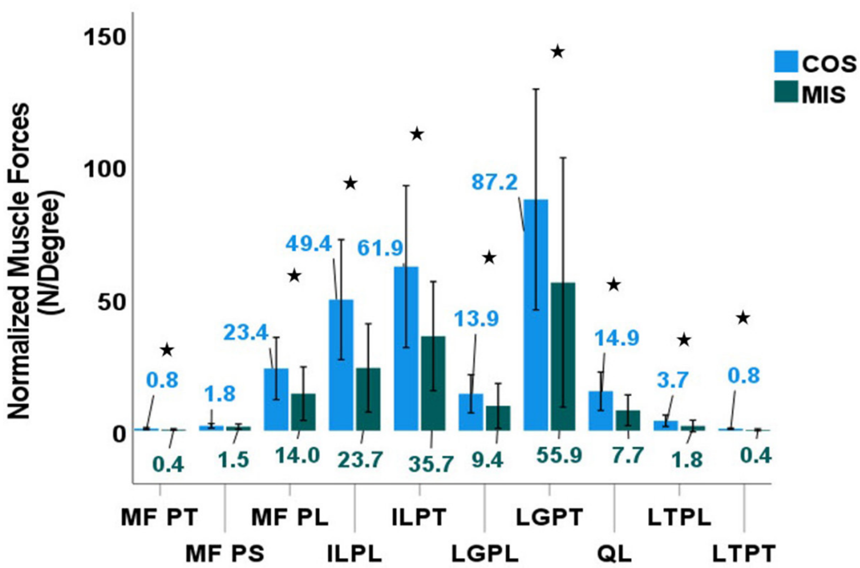

Figure 6: Normalized trunk extensor muscle force with respect to trunk flexion angle between MIS and COS surgical techniques. The Multifidus (MF) in its three compartments (laminar (MF-LP), spinous (MF-SP), and transverse (MF-TP)), the lumbar part of the Iliocostalis (ILPL) a thoracic part (ILPT), the lumbar part of the Longissimus (LGPL) and thoracic part (LGPT), the Quadratus Lumborum (QL), the lumbar part of the Latissimus dorsi (LTPL), and the thoracic part (LTPT) in both Minimal Invasive Surgery (MIS) and Conventional Open Surgery (COS) fusion techniques. *: Significant level

surgical techniques. Most studies have evaluated pre- and post-operative changes in spinal kinematics and muscle forces for various fusion techniques [36, 40, 43-45]. However, studies investigating the impact of muscle injury on spinal biomechanics have often relied on unrealistic scenarios, using data from healthy individuals with similar kinematic patterns [26, 46]. The lack of consideration for patient-specific kinematic data and the use of simplified models (excluding passive tissues) necessitates a more rigorous investigation into the biomechanical factors influencing ASD development in patients undergoing different surgical techniques.

Our findings revealed a significant difference in LPR between MIS and COS groups. This difference was primarily attributed to a 69% decrease in lumbar flexion following COS compared to MIS. Interestingly, pelvic tilt remained relatively unchanged between the two groups, suggesting that the observed differences in LPR were solely due to alterations in lumbar spine mobility. The observed 133% increase in LPR in the MIS group, compared to the COS group, was associated with changes in lumbar range of motion. However, other factors may have also contributed to this difference. Previous studies have proposed two compensatory mechanisms for LPR changes following fusion surgery: 1) Adjacent spinal segments compensate for the restricted ROM at the fused level, maintaining overall lumbar spine mobility [47, 48]. This aligns with findings in the MIS group where ROM remained unchanged. 2) To compensate for reduced motion at the fused segment, the pelvis may exhibit increased movement [49, 50]. Our study revealed similar patterns of pelvic tilt in both MIS and COS groups. Notably, the COS group exhibited a greater reduction in lumbar flexion compared to the MIS group, suggesting that MIS may preserve more functional movement. Given the distribution of lumbar joint flexion angles as a percentage of total lumbar flexion, the flexion angles at the upper and lower levels of the fused region were significantly lower in COS compared to MIS.

Previous studies have shown that alterations in spinal curvature significantly increase intervertebral joint loads, particularly with increased trunk flexion [29, 30, 51]. Consistent with these findings, our analysis revealed a significant increase in compressive loads at the upper fusion level and shear loads at both the upper and lower fusion levels in the MIS group compared to the COS group (Figure 3). To directly compare joint loads between MIS and COS, force values were normalized relative to lumbar flexion angle (Figure 4). By normalizing the data, the confounding effect of lumbar flexion angle was eliminated, enabling a direct comparison between the two surgical techniques. Results showed that inter-joint loads were generally higher in the COS group compared to the MIS group. Notably, the compressive load at the lower adjacent segment was significantly greater by 67% in the COS group. Malakoutian et al. [26] also showed increased loading on fusion levels in open fusion surgery, compared to a muscle-preserving condition. The study by Malakoutian was limited to investigating the effects of different muscle injuries within a single surgical fusion technique, and did not include a comparison between various surgical methods. Additionally, there were no significant differences in upper joint compressive load and shear load between the MIS and COS methods in both upper and lower joints. This finding aligns with the results of Rasmussen et al. who also reported no substantial differences in inter-joint forces between the MIS and COS methods [27].

The analysis of joint moments revealed a significant trend favoring the MIS technique. Compared to MIS group, the COS group demonstrated a marked increase in the normalized values of both total moment and passive moment at both lower (L_3/L_4) and upper (L_5/S_1) spinal levels. Notably, the total moment (active & passive) applied to the L_5/S_1 joint was consistently higher than that applied to L_3/L_4. This finding highlights a key difference: MIS techniques provided sufficient spinal stability under controlled experimental conditions, while exerting lower net moments on adjacent joints compared to traditional open techniques. Furthermore, the MIS method showed significantly lower contributions of compressive forces and passive moments compared to COS. These findings suggest that MIS surgery may impose less stress on adjacent spinal joints, potentially reducing the risk of injury or degeneration.

Spine fusion surgeries can cause muscle injuries, impairing muscle function and altering spinal loading. This disruption affects passive spinal structures, modifies muscle co-contraction patterns, and ultimately influences the distribution of forces within the spine. Previous studies have investigated the impact of surgical muscle injury, characterized by reductions in cross-sectional area [24, 25] or the removal of muscle fascicles [26, 27], on muscle force in the context of spinal fusion. These studies, conducted under controlled conditions with similar ranges of motion, demonstrated an increase in muscle force in the COS group compared to the MIS group. This increased muscle force in the COS group was attributed to compensatory mechanisms aimed at maintaining spinal stability, given the greater extent of muscle damage associated with the COS approach. In contrast, our findings (Figure 5) revealed an increase in muscle force in the MIS group compared to the COS group. It is crucial to acknowledge that previous studies [24, 25, 27] examined muscle force generation within specific tasks and under controlled conditions with similar ranges of motion. Lumbo-pelvic rhythm analysis demonstrated a notable difference between MIS and COS fusion techniques, with patients undergoing MIS exhibiting greater lumbar flexion during the movement cycle. Two primary factors contribute to this observation, firstly, reduced muscle disruption and potential for decreased postoperative pain in MIS may allow for a greater range of lumbar motion. Secondly, a potential compensatory mechanism may be at play. Reduced pain perception due to MIS might lead patients to rely on more trunk flexion to achieve desired movements, possibly due to a subconscious perception of reduced stress on the surgical site (In other words, in the MIS method, the difference in trunk flexion ROM compared to a healthy person is less than COS), Consequently, this increased trunk flexion in MIS patients translates to greater moment arms. A compensatory mechanism may be involved, where reduced pain perception in MIS patients may lead to increased reliance on trunk flexion to achieve desired movements, potentially due to a perceived reduction in stress on the surgical site. This increased lumbar flexion in MIS patients results in larger moment arms acting on the involved muscles, potentially leading to increased external moments and muscle forces compared to COS. To accurately assess muscle force differences between surgical approaches, muscle force values were normalized to lumbar flexion angle to account for the influence of this variable. Consistent with previous observations [25, 35, 40], the analysis revealed significantly higher muscle forces in all trunk extensor muscles (except for the spinous section of the multifidus) in the COS group compared to the MIS group. This finding corroborates previous research and suggests that COS techniques may result in greater overall muscle activation during dynamic tasks. Joint moment analysis showed a clear preference for the MIS technique. Compared to MIS, the COS method demonstrated significantly greater normalized external moment and passive moment at both lower (L_3/L_4) and upper (L_5/S_1) spinal levels. Notably, the external moment (active & passive) applied to the L_5/S_1 joint was consistently greater than that applied to L_3/L_4 joint. This finding highlights a key difference: under identical conditions (normalized values), the MIS technique achieved adequate spinal stability with a lower net moment applied to the joints adjacent to the fusion site. Moreover, the MIS method exhibited significantly lower contributions of compressive forces and passive moments compared to COS. These findings suggest that MIS surgery may exert less stress on adjacent spinal joints, potentially reducing the risk of future injury or degeneration.

Limitation

Given that the shear and compressive loads are significantly influenced by muscle force, anatomy, and kinematic motion, the development of more sophisticated models is warranted. Future models should incorporate factors, such as inter-joint facet forces, the degree of intervertebral disc degeneration, intervertebral disc orientation, the precise rhythm of lumbar lordosis, and different muscle strength in individuals in each surgical method. Furthermore, the current model does not account for the effect of passive tissue (ligaments) rupture and muscle strength reduction in the fusion site, which can occur as a result of muscle injury or atrophy. The model currently only considers the removal of paraspinal muscle fascicle insertions at the fusion site in the open approach compared to MIS.

A limitation of this study lies in its use of the optimization method for muscle force calculation, which neglects the contributions of agonist muscles. Future studies could benefit from employing more sophisticated computational algorithms like Computer Muscle Control to provide more accurate muscle force estimates. Furthermore, to comprehensively assess joint loading, inter-joint forces should be evaluated across a broader range of daily activities involving repetitive movements and high ranges of motion additionally, longer-term follow-up periods exceeding three months would provide more robust data. Given the significant influence of muscle activity on spinal posture and considering the limited availability of inter-joint data, LL and its segmental distribution, as determined by coefficients derived from the literature based on the total lumbar angle during movement, are often used. However, to accurately assess the impact of joint loads on spinal health, it is preferable to determine LL changes directly from MRI images. To investigate the biomechanical effects of pathological conditions, such as those resulting from fusion surgery, the development of novel, high-fidelity MusculoSkeletal Finite Rlement (MS-FE) models of the spine, incorporating detailed and accurate muscle and joint representations, is strongly recommended.

Conclusion

This study demonstrated significant differences in the lumbo-pelvic rhythm between MIS and COS fusion techniques. Alterations in lumbar ROM are a critical biomechanical factor that can influence the development of adjacent segment disease. Notably, the MIS group exhibited minimal alterations in the lumbo-pelvic rhythm during posture maintenance (natural lower back curvature) compared to COS group. Patients undergoing COS displayed a hypolordotic posture, characterized by decreased lumbar lordosis. This altered postural alignment, along with potentially reduced ROM in the COS group, may contribute to increased loading on the lumbar joints, particularly at the lower levels.

Furthermore, iatrogenic injuries caused by the COS surgery technique may have led to increased muscle forces to compensate for compromised spinal stability. This, in conjunction with a potentially greater reliance on passive tissues compared to the MIS method, could contribute to altered spinal biomechanics. These findings suggest that the MIS approach may offer several advantages over COS in mitigating biomechanical factors associated with ASD development. By preserving a more physiological lumbopelvic rhythm and minimizing deviations from the natural lumbar curvature, MIS potentially reduces the overall load placed on lumbar joints.

Acknowledgment

The authors would like to thank Dr. Farhad Tabatabaei Ghomsheh for his help and guidance during this study.

Authors' Contribution

All authors contributed to the study's conception and design. M. Nikkhoo and ChH. Cheng were responsible for data collection. S. Azizi and M. Nikkhoo analyzed and interpreted the data. S. Azizi drafted the manuscript, and M. Nikkhoo critically revised it. All authors approved the final manuscript and agreed to be accountable for all aspects of the work.

Ethical Approval

This study was approved by the Institutional Review Board (IRB) of Chang Gung Memorial Hospital (approval No. 201702031B0) and the Clinical Research Ethics Committee of the Faculty of Medical Sciences and Technologies, Science and Research Branch, Islamic Azad University (IRB No. 104-4548B).

Informed Consent

Written informed consent was obtained from all participants in this study.

Funding

The authors acknowledge the funding supported by the National Science and Technology Council of Taiwan (111-2221-E-182-009-MY3), the Chang Gung Memorial Hospital Research Program (CMRPD1N0191, CMRPG3M0482), and the Healthy Aging Research Center, Chang Gung University, Taoyuan, Taiwan (EMRPD1M0411).

Conflict of Interest

None

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