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Biomechanics

Biomechanical Comparison of 2 Different Pedicle Screw Systems During the Surgical Correction of Adult Spinal Deformities

Mark Driscoll, PEng, PhD[a,*], Jean-Marc Mac-Thiong, MD, PhD[a], Hubert Labelle, MD[a], Shawn Stad, MSc[b], Hassan Serhan, PhD[b], Stefan Parent, MD, PhD[a]

[a]*Spinologics, Inc., 545 Boulevard Crémazie Est, Suite #630, Montréal, Québec H2M 2V1, Canada*
[b]*DePuy Synthes Spine, Inc., 325 Paramount Drive, Raynham, MA 02767, USA*

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Abstract

Study Design: A biomechanical spine model was used to evaluate the impact of screw design on screw−vertebra interface loading during simulated surgical corrections of adult scoliosis.
Objectives: To evaluate differences in screw−vertebra interface forces during adult scoliosis correction between favored angle (FA) screws with extension tabs and standard polyaxial screws while varying deformity severity and curve rigidity.
Summary of Background Data: Pedicle screws enable surgeons to safely and effectively realign spinal deformities. The risk of perioperative screw pullout increases when presented with adult deformities that have less flexible spines and lower bone mineral density. An FA screw with reduction tabs is believed to enable surgical techniques permitting load distribution on multiple screws, thereby reducing screw pullout potential.
Methods: The researchers constructed 3 finite element spine models from adult scoliosis patients. Mechanical properties of intervertebral discs were modeled to reflect less flexible adult spines and their stiffness was varied to evaluate impact on screw−vertebra forces. Models simulated scoliosis surgery according to clinical data using FA or polyaxial screws. Forces measured at the screw−vertebra interface were monitored and compared for each patient with FA and then polyaxial screws.
Results: Simulations using FA screws reduced screw−vertebra interface forces significantly compared with polyaxial screws. Favored angle screws caused 18%, 14%, and 16% reductions in peak forces and 29%, 35%, and 22% reductions in average forces compared with polyaxial screws for patients 1, 2, and 3, respectively. Favored angle screws also provided consistent relative reduction in average forces by 28% when varying properties of intervertebral discs among 8, 10, and 12 MPa.
Conclusions: Using a virtual finite element platform, FA screws reduced screw−vertebra interface forces encountered during simulated correction of less flexible adult scoliosis compared with standard polyaxial screws. These results show a potential benefit of using this modified screw design to reduce screw−vertebra forces and potential intraoperative pullout failures.
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Keywords: Scoliosis; Biomechanical model; Pedicle screw; Pullout

Introduction

Scoliosis deformities are diagnosed and treated according to their irregular spinal curvature. In the event that the spinal deformity progresses significantly or causes major symptoms such as pain, disability, or neurologic impairment, surgical interventions may be required. Correspondingly, the surgical goals may include reestablishing physiological spinal alignment and balance, alleviating pain, improving function, and preventing further neurologic deterioration. Current medical technologies and corresponding surgical techniques employ pedicle screws as a means to securely anchor a rigid spinal rod between misaligned vertebrae. This process enables controlled restoration of spinal alignment through the artificial coupling of adjacent spinal segments. Despite the evolution of spinal instrumentation over the past 5 decades, surgical objectives of spinal realignment remain the same and

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*Corresponding author. Spinologics, Inc., 545 Boulevard Crémazie Est, Suite #630, Montréal, Québec H2M 2V1, Canada. Tel.: (514) 389-1331; fax: 1 (888) 988-2747.

E-mail address: mdriscoll@spinologics.com (M. Driscoll).

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consequently oblige the use of forceful surgical maneuvers to counter otherwise irregular physiological forces. These forceful corrective maneuvers involve some of the highest instrumentation forces among orthopedic procedures.

Undesirable complications are seldom avoided when surgical forces exceed physiological limits. Screw pullout is a notable complication that has long been the subject of investigation. Pullout forces are quantified in the axial direction at the screw−vertebra interface of the screw shaft; upon exceeding a threshold, dislodgment occurs, causing failure of the instrumentation construct. This threshold value vastly varies within the literature from as low as 100 N to as high as 2,000 N [1,2] and differs according to screw characteristics such as length, diameter, insertion angle, and thread features [3-7]. Another important patient characteristic affecting the pullout threshold is bone mineral density, which has been shown to drastically decrease the amount of force required for screw pullout [2,8,9].

To curtail intraoperative screw pullout failure, new pedicle screw systems have been devised to enable surgical techniques offering improved rod capture and shared reduction forces. Among these, favored angled (FA) screws with reduction tabs have been shown to reduce the screw−vertebra interface forces significantly compared with standard polyaxial screws during simulated adolescent scoliosis surgery [10]. In that study, the FA screw advantageously decreased forces at the screw−vertebra interface and was more forgiving in cases of screw misalignment [10]. However, the results from that study may not be translatable to a stiff osteoporotic spine commonly seen in the adult population.

Adult deformity surgical corrections differ because they often have more prominent lumbar deformities and less flexible spines. It is therefore conceivable that larger corrective forces may be required. In addition, this population often has reduced bone mineral density of the vertebrae, which reduces screw pullout thresholds [8,10,2]. The purpose of this biomechanical study was to evaluate screw−vertebra interface forces encountered during simulated surgical correction of adult deformities employing a clinically based finite element model (FEM) of the spine using FA or standard polyaxial screws.

Materials and Methods

Biomechanical model

The researchers constructed 3 custom osteo-ligamentous spine FEMs using preoperative clinical data from 3 adult scoliosis patients, using ANSYS 14.5 software (Canonsburg, PA). Clinical data were acquired and maintained in accordance with the approval of the institutional ethical review committee. The volumetric model included the thoracic and lumbar spine, the sacrum and pelvis, and all corresponding spinal ligaments (Fig. 1). The vertebrae, pelvis, and sacrum were modeled as rigid bodies whereas the intervertebral discs were flexible, exhibiting a bulk modulus of 10 MPa to reflect the beginning of grade 2 degeneration (Nachemson score) [11,12]. This modulus was later modified to be more flexible (8 MPa) or rigid (12 MPa) for patient 1 to further analyze the impact of disc rigidity in the adult population on this study (Table 1). The

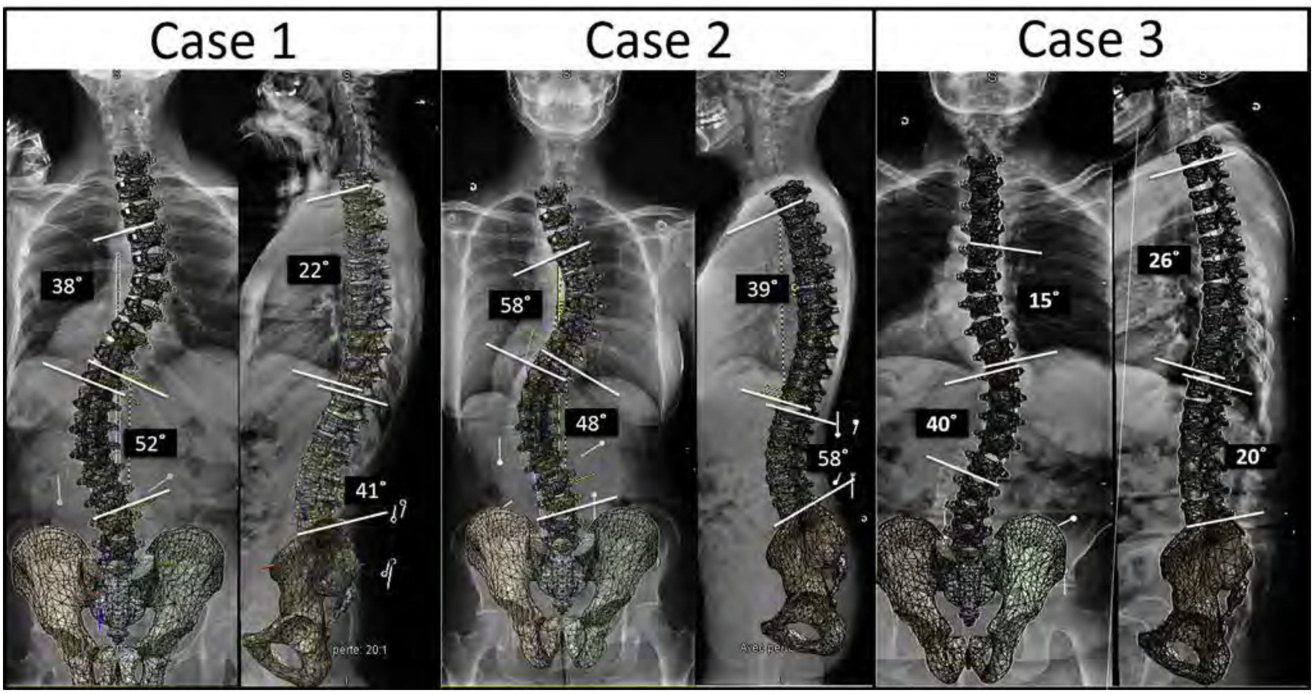

Fig. 1. Posterior and lateral views of the finite element model of the spine superimposed over the preoperative radiographs of patients 1, 2, and 3.

Table 1
Material properties and element types of finite element model.

Body	Modulus/ rigidity	Element type
Vertebral bodies, pelvis, and spinal cages	Rigid	Center of gravity pilot node with outer target elements
Annulus fibrosus	8–12 MPa (adjusted)	Solid 185 Hex
Nucleus pulposus	2 MPa	Solid 185 Hex
Anterior longitudinal ligament	23.75 N/m	Link 180
Posterior longitudinal ligament	26.15 N/m	Link 180
Interspinous ligament	9.8 N/m	Link 180
Ligamentum flavum	22.6 N/m	Link 180
Capsular ligament	23.7 N/m	Link 180
Spinal rod, − 5.5 mm, cobalt chrome	213 GPa	Beam 188
Screw, titanium	110 GPa	Solid 185 Hex

spinal ligaments were modeled as springs capable of exhibiting tension only and were estimated at 23.75, 26.15, 9.8, 22.6, and 23.7 N/mm for the anterior longitudinal, posterior longitudinal, interspinous, ligamentum flavum, and capsular ligaments, respectively [13]. The biomechanical model and methods of analyses used here were previously shown to be effective for simulations of scoliosis surgeries and underwent clinical validation [10,14].

Spinal instrumentation

Two different spinal screws were modeled for comparison. The FA and polyaxial screws were modeled identically and differed only by 2 specific technical characteristics. First, the FA screw had a biased lateral head pivot of 54° and a medial pivot of 24°, whereas the polyaxial screw had a uniform conical head pivot of 30°. Second, FA screws were modeled to include breakaway extension tabs, thus enabling initial rod capture at a distance of 20.5 mm, whereas the polyaxial screw necessitated full reduction of the rod to its screw head before rod capture (Fig. 2). Both screws were modeled as rigid bodies, effectively enabling the detailed analyses of forces occurring at the screw–vertebra interface. Screw shaft sizes varied from 5 × 35 to 6 × 40 and 6 × 45 mm in correspondence to the pedicle and vertebral body dimensions of respective patients' spines and the instrumented levels. The iliac screw was modeled as a 7.5 × 70 polyaxial screw using a 20-mm connector for patients 1 and 3. Because the sacroiliac joint was modeled as fixed, the iliac screw did not affect the overall construct. The contact areas defining all screw–vertebra interfaces were modeled as rigidly bonded.

The spinal rod was modeled with a cross-sectional diameter of 5.5 mm and assigned a modulus of 213 GPa, consistent with cobalt chrome. The perioperative sagittal shape assigned to the modeled spinal rod was formed according to the surgeon's guidance regarding the desired level of sagittal manipulation. The rods used were identical when exploring FA and polyaxial screws for each patient.

Patients 1 and 3 had spinal cages positioned between the L4–L5 and L5–S1 levels. The presence of these spinal cages was simulated by volumetrically inserting a bullet cage with a 5° lordotic angle, 23 mm long and 10 mm thick (DePuy Synthes Spine, Raynham, MA). The cages were modeled as rigid bodies confined to the bordering vertebrae

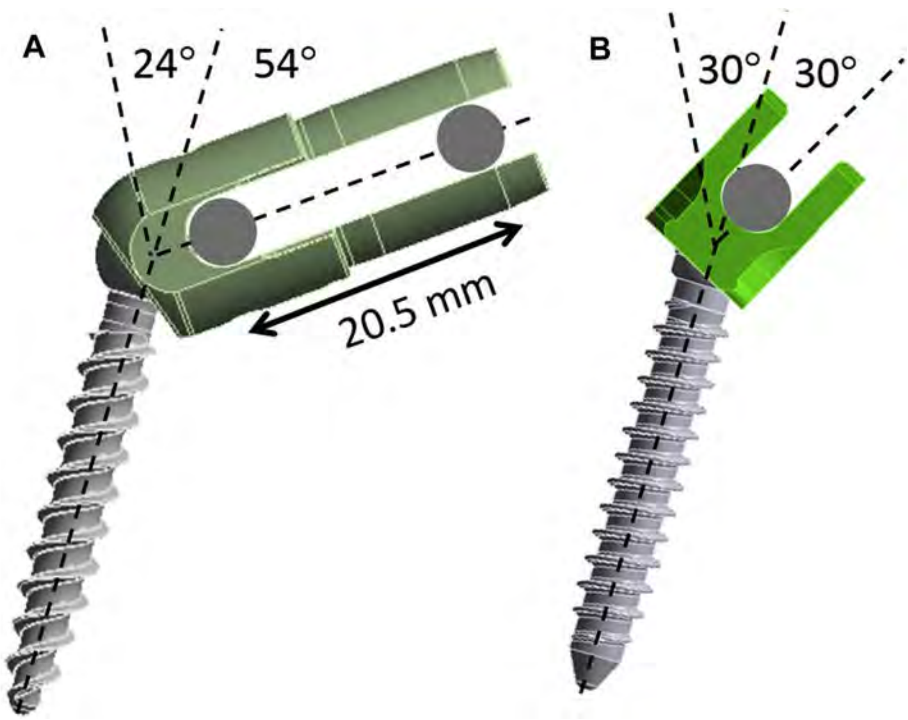

Fig. 2. Differences in screw head pivot and rod capturing distance between (A) favored angle and (B) polyaxial screws as simulated in the model.

with a joint providing limitation in compression and restrictive motion in other degrees of freedom via a nested bushing enabling control of the restrained motion. The transforaminal lumbar interbody fusion cage was inserted at a left diagonal and the bushing conditions were tailored to govern relative movement between adjacent vertebrae in accordance with those reported for transforaminal lumbar interbody fusion cages with unilateral pedicle screw fixation [15].

Surgical simulation

All 3 simulated patients underwent segmental translation of the concave rod from caudal to cranial screws both clinically and in the modeled simulation using only FA screws. The simulation was subsequently repeated using only polyaxial screws. The only changes in the simulated surgical procedures between the use of FA and polyaxial screws corresponded to their technical differences. For simulation using the FA screw, the biased lateral head pivot of 54° enabled a more lateral reduction of the rod to the screw base. Moreover, the FA screw's extension tabs offered the combined ability to capture the rod at a distance by all screws before conjoined reduction of the rod to the screw head. In contrast, for simulations using the polyaxial screw, rod capture in the screw head occurred at a maximum 30° lateral inclination and at a distance bordering the base of the screw head (Fig. 2). Once all screws captured the rod, for both FA and polyaxial screw simulations, a small rod rotation emulating the clinical surgery was performed to manipulate spinal alignment and impose desired sagittal curvatures (Fig. 3).

To simulate the surgeon's action of joining the rod to the screw, a series of custom coded artificial connections and nested degrees of freedom was used to dictate the motion of the rod with respect to the screw heads [14]. The spine's displacement in reaction to the simulated surgical maneuvers was governed by the intervertebral disc properties and presence of spinal ligaments. Forces were monitored at the screw–vertebra interface of all screws during each step of the simulation. The surgery was simulated in a series of intermittent steps, as performed clinically, with each step's residual results carrying into subsequent analyses until the simulation was complete.

Validation

The model was previously evaluated as a feasible means to simulate scoliosis surgery [10,14]. To ensure further clinical corroboration, patient postoperative data were maintained consistent to the simulated surgical outcomes. In addition, stresses measured in the intervertebral discs

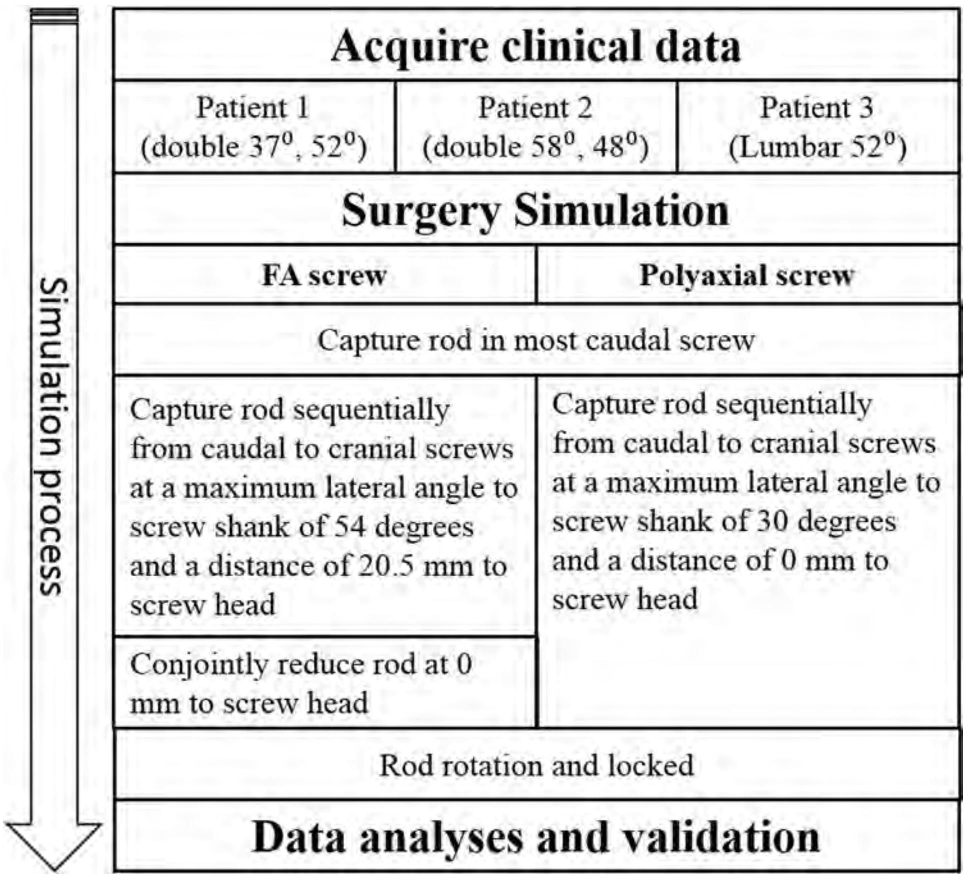

Fig. 3. Order of surgical simulation steps for favored angle and polyaxial screws. Pre-op, preoperative; Peri-op, perioperative; Post-op, postoperative.

and screw–vertebra interface forces were compared with reported pullout forces in literature.

Results

Each completed FEM of the spines was composed of 89 volumetric bodies (vertebrae, pelvis, sacrum, intervertebral discs, screw shafts, screw heads, artificial connections to rod, and spinal rod), 99 tensional elements (ligaments), 46 joints (artificial connection to rod, screw–vertebra interface, spinal cages, and bushings), and 135 independent coordinate systems. Preoperative spinal profiles of the constructed model adhered well to patients' clinical data (Fig. 1, Table 2). Evaluation of intervertebral disc Von-Misses stress levels in non-instrumented discs agreed with prior validation processes of the model [14]. Maximum stress levels during the simulation fluctuated from 0.5–2.3 to 0.1–0.6 and 0.10–0.80 MPa for patients 1, 2, and 3, respectively. Results of local relative motion between vertebrae adjacent to the spinal cages (L4–L5 and L5–S1 for patients 1 and 3) provided a confined degree of freedom of ± 2.6° in flexion and extension, ± 0.4° in lateral bending, and ± 3.6° in axial, which are in relative agreement with prior studies considering the differences in experimental conditions [15].

Postoperative results of the simulated surgery corroborated with the clinical data within the targeted 5° excluding the adopted hyperkyphosis in patient 3, which was not predicted with such accuracy (Fig. 4, Table 2). The average difference between the clinical and FEM data was 3.1° and 4.1° in the coronal and sagittal planes, respectively. No significant differences were observed in spinal profiles or angular differences between simulations using the FA or polyaxial screws.

Measures of peak and average axial forces monitored at the screw–vertebra interfaces throughout the surgical simulation showed a reduction when using FA screws compared with polyaxial screws. Peak force magnitudes were consistent with or marginally greater than similar studies performed on adolescent models [10,14,16,17]. Patient 1, who had pedicle screws at T6 and from T8 to S1, had a reduction of 18% in peak and 29% reduction in average screw–vertebra forces when using FA screws over polyaxial screws. Patient 2, who had screws from T2 to L3, and patient 3, who had screws from T10 to S1, respectively, experienced 14% and 16% reductions in peak screw–vertebra forces and 35%

Table 2
Preoperative and postoperative measures of spinal profiles (in degrees) for clinical and finite element model (FEM) data simulated using favored angle (FA) or polyaxial screws.

	Patient 1					Patient 2					Patient 3				
	Preoperative		Postoperative			Preoperative		Postoperative			Preoperative		Postoperative		
	Clinical	FEM	Clinical	FEM		Clinical	FEM	Clinical	FEM		Clinical	FEM	Clinical	FEM	
				FA	Polyaxial				FA	Polyaxial				FA	Polyaxial
Thoracic curve	38	39	18	23	21	58	56	23	28	28	15	15	10	12	12
Thoraco-lumbar curve	52	49	18	20	20	48	47	22	23	21	40	38	18	22	23
Kyphosis	22	26	44	46	47	39	39	55	52	51	26	25	61	53	52
Lordosis	41	41	41	43	41	58	53	55	50	50	20	23	48	43	45

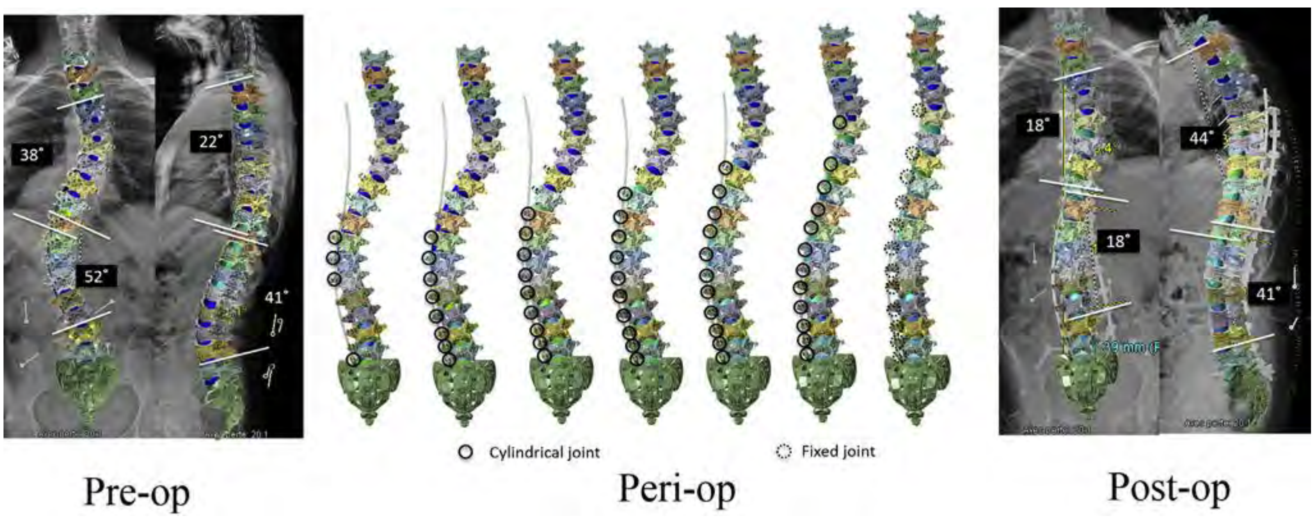

Fig. 4. Demonstration of the surgical simulation steps and order exemplified for patient 1 (pelvis and ligaments removed for visualization).

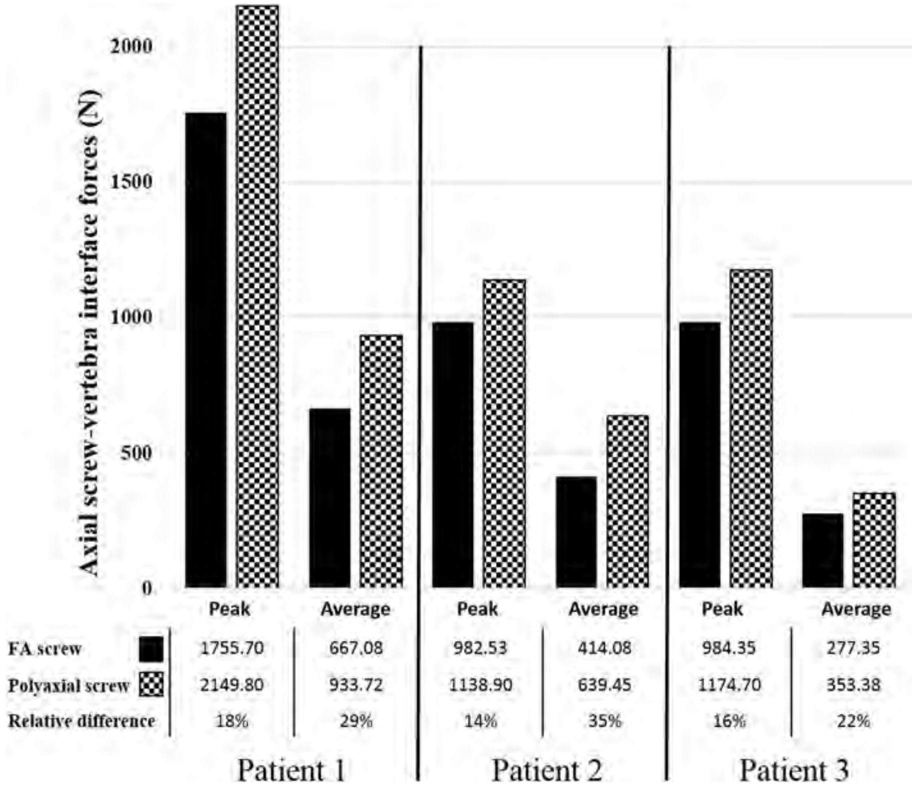

Fig. 5. Peak and average axial screw–vertebra interface forces measured during all steps of the simulated surgery of each patient.

and 22% reductions in average axial forces (Fig. 5). The simulated or surgical steps at which peak screw–vertebra forces occurred differed when using FA or polyaxial screws (simulated steps, Fig. 3). Using FA screws, peak axial forces occurred during simulation of initial rod capture, rod reduction, and rod rotation at 30%, 45%, and 25% of the time, respectively. Conversely, with the polyaxial screws the simulated peak axial force occurred during initial rod capture at a rate of 74% whereas the peak took place during rod reduction and rod rotation at 17% and 9% of the time.

Upon varying the properties of the intervertebral discs between 8, 10, and 12 MPa, the measures of average screw–vertebra axial forces increased significantly (Table 3). More specifically, average axial forces increased from 560 to 778 N for the FA screws whereas polyaxial screws jumped from 783 to 1079 N upon increasing the modulus of the intervertebral disc from 8 to 12 MPa.

Table 3
Changes in average screw–vertebra interface forces measured during simulated surgery as a result of varied intervertebral disc (IVD) properties for favored angle and polyaxial screws.

	Average screw–vertebra interface force, N		
	IVD 8 MPa	IVD 10 MPa	IVD 12 MPa
Favored angle screw	560.90	667.08	778.02
Polyaxial screw	783.24	933.72	1,079.20
Relative difference (%)	28%	29%	28%
Absolute difference, N	222.34	266.64	301.19

Whereas the absolute bone–screw interface loading increased proportionately to the curve stiffness of the spine, the relative reduction in average forces provided by the FA screw versus the polyaxial screw remained consistent at approximately 28%.

Discussion

Safe and effective correction of scoliosis deformities is a clinical objective that necessitates carefully orchestrated surgical maneuvers. Today, many spinal implant designs provide surgeons with a plethora of instrumentation options. This study sought to objectively compare 2 of these options, FA and polyaxial screws. A previously validated FEM of the spine demonstrated a reduction in axial screw–vertebra interface loads with FA screws compared with polyaxial screws [10]. Such benefits are believed to stem from improved screw head excursion and control of the spinal rod enabling a gradual and balanced distribution of loading across the pedicle screws simultaneously at several levels. Other screws offer extension tabs; however, the FA screw is the only one enabling an augmented and biased lateral pivot of its head, which proved advantageous when using segmental translation techniques as explored in previous and current studies.

In contrast to prior studies using this model [10,14], the results of this study suggest an increase in the forces required to correct adult deformities compared with adolescent scoliosis. This increase is believed to result from the use of stiffer spine models simulated by greater mechanical properties of the intervertebral discs. Moreover, additional constraints imposed on vertebrae adjacent to spinal cages may have contributed to local increases in peak screw−vertebra interface forces. Finally, curve location of the simulated patients did not correspond well with the kyphosis and lordosis of the spinal rod as set out by the surgeon. Consequently, screw−vertebra interface forces in this study were comparatively elevated, which may prove important considering the possibility of adults having osteopenia and, correspondingly, a reduction in pullout strength at the vertebra−screw interface [8,9]. Therefore, achieving surgical realignment with reduced screw−vertebra interface forces on adult patients, as provided by the FA screw, may prove particularly useful in practice.

When evaluating the sensitivity of the results on spinal rigidity, one may observe that screw−vertebra interface forces increased correspondingly with the intervertebral discs properties (Table 3). This correspondence suggests that spinal rigidity is an important factor to consider when evaluating the risk of screw pullout. Alternatively, changes in bone density and osteoporosis may also increase the risk of screw pullout. Results comparing the FA and polyaxial screws showed consistent relative reduction in screw−vertebra interface forces with FA screws compared with polyaxial screws regardless of the increase of spine stiffness evaluated by increases in intervertebral disc stiffness. This speaks to the robustness of the FEM and further highlights the reliable reduction of screw−vertebra forces advantageously provided by the FA screw.

Studies using FEMs must be conservative in their conclusions. Limitations of this model arise when attempting to simulate the action of adjoining the rod to the screw head, which in practice is an intricate process during which the surgeon's tactile feedback is governed by experience. The model employs a straight line approach joining the rod to the screws, which conceptually may be assumed as the surgeon's visual guide. The authors also recognize that the spinal rod and screw attachment sequence may differ between surgeons as well as from those employed here and in previous analyses [10]. Furthermore, in situ bending of the rods, commonly used to reestablish desired sagittal curves lost to rod yielding or flattening during derotation, was not explored because little variation is expected between screws after rod capture and reduction. However, additional studies may be needed to evaluate the benefits of first performing rod derotation and then sequentially reducing the rod toward the screw heads, which may decrease rod yielding resulting from potentially diminished point loads. Under such circumstances, the authors hypothesize that the point load reduction granted by the FA screw, found here and in prior studies [9], could result in less rod yielding and loss of sagittal control. In addition, other screw types, such as monoaxial screws, might also have been evaluated but the more commonly used polyaxial screws were chosen for comparison with FA screws. An alternative restriction of this FEM is the ability to predict the behavior of the spine outside the region being instrumented. The response of the patient to the spinal construct outside the instrumented region may not necessarily coordinate with the simulated perioperative reaction forces, as observed in the kyphosis of patient 3, who seemed to have developed a junctional kyphosis. Vertebrae were also modeled as rigid bodies and thus were not deformable; consequently, the results at the screw−vertebra included only reaction forces and not stresses. Furthermore, this analysis was limited to interpretations of axial forces and did not explore moments at the screw−vertebra interface, which could be the topic of future studies. To alleviate discrepancies caused by such assumptions, this study used clinical data to corroborate results, whereas data were monitored and supported by published literature. Nevertheless, results advocated here confidently revolve around relative comparisons made using an objective experimental platform.

Consistent with complementary studies, this analysis demonstrated the ability of the FA screw to reduce screw−vertebra forces required for the surgical correction of scoliosis compared with polyaxial screws. More specifically, the FA screw proved to be successful at reducing screw−vertebra interface forces in adult scoliosis when presented with less flexible spines. The FA screw may be advantageous in preventing screw pullout when the surgeon is presented with adults demonstrating osteopenia and stiff curves.

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