Original Article

The accuracy of robot-assisted S2 alar-iliac screw placement at two different healthcare centers

Nathan J. Lee[1], Asham Khan[2], Joseph M. Lombardi[1], Venkat Boddapati[1], Paul J. Park[1], Justin Mathew[1], Eric Leung[1], Jeffrey P. Mullin[2], John Pollina[2], Ronald A. Lehman[1]

[1]Department of Orthopaedics, Columbia University Medical Center, The Och Spine Hospital at New York-Presbyterian, New York, NY, USA; [2]Department of Neurosurgery, State University of New York, Buffalo, NY, USA

Contributions: (I) Conception and design: NJ Lee, A Khan, J Pollina, RA Lehman; (II) Administrative support: JM Lombardi, JP Mullin, J Pollina, RA Lehman; (III) Provision of study materials or patients: A Khan, JM Lombardi, JP Mullin, J Pollina, RA Lehman; (IV) Collection and assembly of data: NJ Lee, A Khan, V Boddapati, PJ Park, J Mathew, E Leung; (V) Data analysis and interpretation: NJ Lee, A Khan, V Boddapati, PJ Park, J Mathew, E Leung; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Nathan J. Lee, MD. Columbia University Medical Center, 161 Fort Washington Avenue, New York, NY 10032, USA. Email: njl2116@cumc.columbia.edu.

Background: Current literature on robot-assisted S2 alar-iliac (S2AI) screw placement shows favorable outcomes and screw accuracy; however, the data is limited by a few retrospective, single-surgeon studies. To the author's knowledge, this is the first multicenter study which evaluates the accuracy of robot-assisted S2AI screws.

Methods: Adult (≥18 years old) patients who underwent robot-assisted S2AI screw placement from 2017–2019 were reviewed. All surgeries used the same proprietary robotic guidance system, Mazor X (Mazor Robotics Ltd).

Results: A total of 65 screws were assessed in 31 patients. The mean follow-up ± standard deviation was 362±190 days (minimum was 90 days). The mean age was 61.1±11 years old, and 54.8% (n=17) of patients were female. Nearly half of the patients had a primary diagnosis of degenerative scoliosis (48.4%, n=15). Other diagnosis included pseudarthrosis (22.6%, n=7), degenerative disc disease (16.1%, n=5), and high-grade spondylolisthesis (12.9%, n=4). The mean length and diameter of screws were 84.6±6.1 mm and 8.4±0.7, respectively. The mean axial and sagittal angles were 50.0±6.3 and 24.0±10.5, respectively. The overall screw accuracy was 93.8% (n=61). There were four iliac cortex breaches (anterior =3, inferior 1) with a mean breach distance of 3.5±3.2. No statistically significant differences in screw length, diameter, axial angle, and sagittal angle were observed between screws with and without a breach. No intraoperative neurologic, vascular, or visceral complications from the S2AI screw were observed. No post-discharge wound complications, screw prominence issues, or revision of S2AI screws were observed during the study's follow-up period.

Conclusions: Robot-assisted S2AI screw placement was found to be safe and accurate in this multicenter study. This is largely attributed to the versatility of the robotic guidance software that allows for detailed and precise preoperative and intraoperative planning.

Keywords: Robot-assisted spine surgery; robotic spine surgery; S2 alar-iliac (S2AI); sacral alar iliac screw; spinopelvic fusion

Submitted Feb 08, 2021. Accepted for publication Apr 07, 2021.
doi: 10.21037/jss-21-14
View this article at: https://dx.doi.org/10.21037/jss-21-14

Introduction

Spinopelvic fusion is used to enhance the stability and improve caudal fixation, especially for long fusion constructs. Traditionally, the iliac screw has demonstrated excellent biomechanical stability and lower pseudarthrosis rates; however, complications such as screw site pain and wound complications have led to alternative techniques, such as the S2 alar-iliac (S2AI) screw (1-4). In comparison to conventional methods of spinopelvic fixation, the S2AI screw technique uses a more medial starting point which results in a lower profile for the screw head and is considered to have comparable biomechanically stability since the screw traverses through the sacral ala, sacroiliac joint, and the ilium where it engages with dense bone above the sciatic notch (5,6). Furthermore, current literature has found that the S2AI screw is associated with decreased tissue dissection, less implant prominence, better alignment with proximal pedicle screws which eliminates the need for additional connectors, and lower mechanical failure (7,8).

S2AI screws can be reliably and safely performed through a free-hand technique by experienced surgeons; however, screw accuracy relies heavily on visible and palpable anatomical landmarks. In situations where there is significant spinal deformity or altered anatomy, robot-assisted guidance may provide a technical advantage. Another concern is the amount of potential radiation exposure for the patient and surgical team when using more conventional techniques (e.g., fluoroscopy) (9). Some studies have shown a reduction in surgeon radiation exposure during robot-guided lumbar fusion surgery (10,11). In addition, matching preoperative CT with intraoperative fluoroscopic images has been shown to improve the visualization of osseous structures, increase precision of screw insertion for spinopelvic fixation, and decrease fluoroscopic time (12).

Currently, only a few retrospective studies have reported on the screw accuracy and outcomes of robot-assisted S2AI fixation. Although these early studies show promising results, the data is limited to single-surgeon, single-center studies. To the author's knowledge, this is the first multicenter study which evaluates the accuracy and safety of robot-assisted S2AI screws.

We present the following article in accordance with the STROBE reporting checklist (available at https://dx.doi.org/10.21037/jss-21-14).

Methods

Patient selection

We reviewed a consecutively-collected database of adult patients (≥18 years old) at two separate hospital centers who underwent a robot-assisted S2AI screw fixation at two different academic medical centers between 2017 and 2019. All surgeries used the same proprietary robotic guidance system, Mazor X (Mazor Robotics Ltd). Two independent surgeons, who were not directly involved in the primary care of these patients, reviewed the intraoperative fluoroscopic images and O-arm CT scans of each patient. To more accurately measure screw trajectory and screw breaches, particularly for patients with irregular anatomy, the Vitrea Core (Vital Images, Minnetonka, MN) interactive imaging software was used. This software allows for three-dimensional analysis based on CT or O-arm imaging. Patients who did not have or were missing an intraoperative O-arm scan were excluded. All O-arm and CT scans included the pelvis. Other perioperative data, including demographics (e.g., age, gender, comorbidities, primary diagnoses) and operative factors (e.g., screw, intra- and postoperative complications) were collected from the electronic medical record. Patients with missing data were excluded from analysis. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by ethics board of Columbia University and State University of New York (AAAT1470) and individual consent for this retrospective analysis was waived.

Robotic system

The Mazor X System is the Mazor's third-generation spine robot, replacing the Renaissance after its FDA approval in 2016 (13). Similar to prior systems, the Mazor X is comprised of a workstation and surgical arm, which is mounted to the patient and the operating table. In comparison to prior systems, the Mazor X uses an integrated optic camera which enables an intraoperative three-dimensional visual scan of the operating room environment. This allows the robot to better self-detect its location and potentially reduce collision with the patient or other elements in the surgical field. Furthermore, the Mazor X assesses each vertebral body independently to further improve accuracy. Finally, the robotic arm is designed to

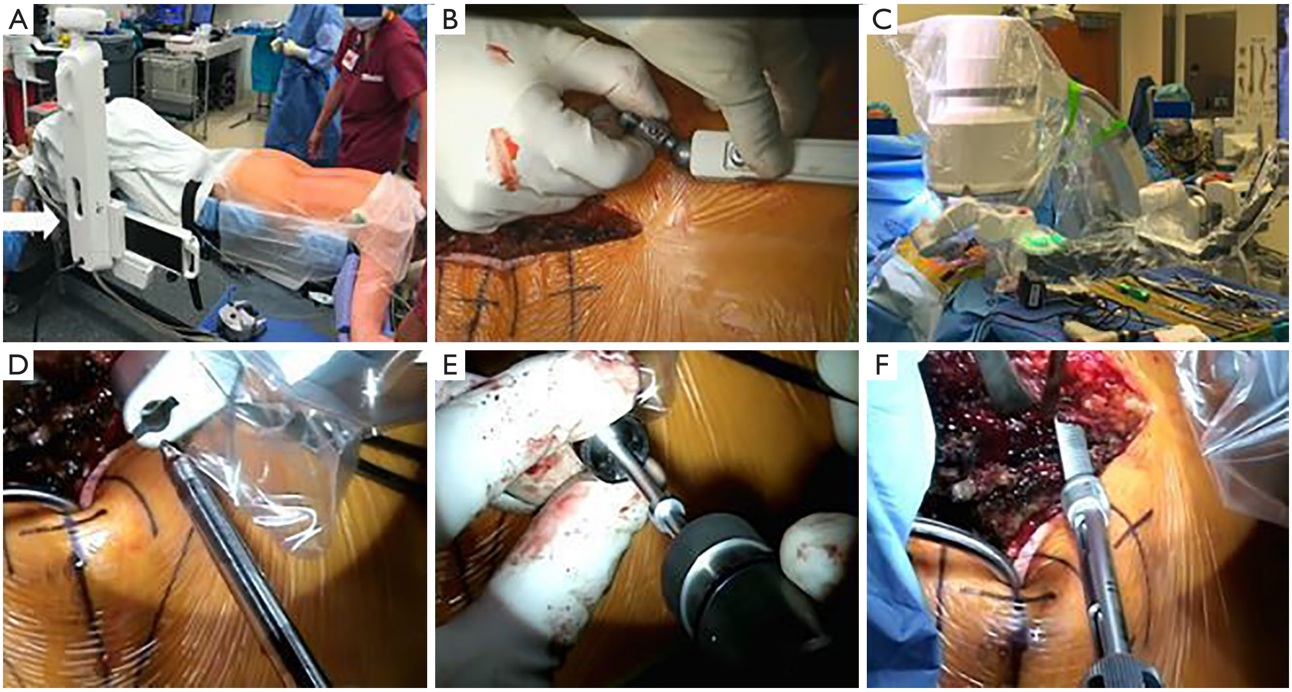

Figure 1 An illustrative example of the operative workflow for robot-assisted spine surgery. (A) Patient is positioned prone and the robot is mounted to the OR table; (B) a pin is placed into the PSIS and connected to the robot; (C) intraoperative fluoroscopy is performed to register the robot; (D) trocars are placed through the cannula to dock onto the entry point; (E) a drill is used to create a pilot hole and a k-wire is placed; (F) after tapping, the screw is placed.

be serial, rather than parallel in order to increase the range of motion and reduce the need for additional surgical tools which may increase the risk for human error and prolong operative time.

Robotic surgical technique

A major advantage of robot-assisted spine surgery is the planning software. Prior to surgery, preoperative thin cut (1 mm) CT imaging can be uploaded to the interactive robotic software to preoperatively plan optimal screw size, diameter, and trajectories in the sagittal, coronal, and axial planes. Alternatively, surgical planning can be performed intraoperatively with an O-arm (Medtronic PLC, Medtronic Inc., Dublin, Ireland) without obtaining a preoperative CT scan. The planning software provides the surgeon with a three-dimensional assessment of each vertebra using a proprietary anatomical landmark recognition algorithm to improve accuracy and predictability.

After the patient is appropriately positioned in the prone position, a Schantz pin is placed into the right posterior superior iliac spine. The surgical arm is mounted to the operating table by a bed frame adapter and connected to the patient via a bone mount bridge. For preoperatively planned cases, anterior-posterior and oblique/lateral fluoroscopic images are taken to register the robot and appropriately synchronize the pre-operative CT imaging with the patient. According to the planned trajectory, the cannulated robotic arm automatically moves to the targeted entry point. A drill guide is placed through the cannula and securely seated onto the surface of the target anatomy via the tines of the drill guide. A drill is used to create a pilot hole and a k-wire is placed a few millimeters into bone so that it is not inadvertently displaced as a trocar is removed. Once the k-wire is securely placed, the screw hole is tapped and a ball-tipped probe is used to ensure no bony breach and confirm screw length. Finally, the screw is placed and subsequent related procedures are performed (*Figure 1A-1F*). An O-arm CT scan is performed to ensure adequate placement of all screws.

Screw analysis

Intraoperative O-arm CT scans were reviewed using built-

Table 1 Patient demographics, comorbidities, and perioperative factors

Variable	Number (%)
Total number of patients	31
Female	17 (54.8)
Age, mean ± SD	61.1±11
American Society of Anesthesiologists >2	11 (35.5)
Body mass index >30 kg/m^2	8 (25.8)
CCI, mean ± SD	2.0±1.1
Prior spine surgery	17 (54.8)
Prior/current smoker	11 (35.5)
Osteoporosis	15 (48.4)
Diagnosis	
Degenerative scoliosis	15 (48.4)
Pseudarthrosis	7 (22.6)
Degenerative disc disease	5 (16.1)
High-grade spondylolisthesis	4 (12.9)
Total number of levels fused, mean ± SD	9.9±4.1
Upper instrumented vertebrae	
C7	1 (3.2)
T2–T5	7 (22.6)
T6–T9	1 (3.2)
T10–T12	18 (58.1)
L4	4 (12.9)

SD, standard deviation.

in radiology tools including the Vitrea Core software, which enabled the postoperative assessment of screw trajectory in the axial, sagittal, and coronal planes simultaneously. The axial trajectory of the screw was measured as the angle between the longitudinal axis of the screw and the line connecting the PSIS in the axial plane. The sagittal screw trajectory was measured as the angle between the longitudinal axis of the screw and the horizontal line. These measurements were consistent with those already published in literature which used the Vitrea Core software (14). Screw accuracy was measured according to the Gertzbein and Robbins classification (15). If there was no breach, the screw was classified as a Grade A; <2 mm deviation was a Grade B, <4 mm deviation was a Grade C, <6 mm deviation was a Grade D, and >6 mm deviation was a Grade E. Both the direction of the breach and the breach distance were recorded as well.

Statistical analysis

The chi-square test and *t*-test were used to compare categorical and continuous variables, respectively. Statistical significance was defined as P value <0.05. SAS Studio Version 3.4 (SAS Institute Inc., Cary, NC) was used for all statistical analyses.

Results

A total of 65 screws were assessed in 31 patients. The mean follow-up ± standard deviation was 362±190 days (minimum follow-up was 90 days after the index discharge date). The mean age was 61.1±11 years old, and 54.8% (n=17) of patients were female. Nearly half of the patients had a primary diagnosis of degenerative scoliosis (48.4%, n=15). Other diagnoses included pseudarthrosis (22.6%, n=7), degenerative disc disease (16.1%, n=5), and high-grade spondylolisthesis (12.9%, n=4). The mean number of total levels fused was 9.9±4.1 and more than half (54.8%, n=17) had a prior spine surgery. The most common upper instrumented vertebrae were in the upper thoracic (T2–T5: 22.6%, n=7), lower thoracic spine (T10–T12: 58.1%, n=18), and lumbar (12.9%, n=4) (*Table 1*).

The mean length and diameter of screws were 84.6±6.1 mm and 8.4±0.7, respectively. The mean axial and sagittal angles were 49.6±5.6 and 24.0±10.5 degrees, respectively. The overall screw accuracy was 93.8% (n=61). Although the axial angle appeared larger for breached screws (53.5±4.6 degrees) than non-breached screws (49.3±5.7 degrees), this was not statistically significant (P=0.160). Furthermore, no statistically significant differences in screw length, diameter, and sagittal angle were observed between screws with and without a breach (*Table 2*). There were four iliac cortex breaches (anterior =3, inferior 1) with a mean breach distance of 3.5±3.2 mm. Three screw breaches were classified as grade B; however, one was a grade E and was revised appropriately during the same index surgery (*Table 3*). *Figure 2* is an example of a cortical breach. The pre- and postoperative radiographs of a typical patient who underwent a T10 to pelvis fusion for degenerative scoliosis are illustrated in *Figure 3*.

No intraoperative neurologic, vascular, or visceral complications from the S2AI screw were observed. During the study's follow-up period, two patients were readmitted

Table 2 S2AI screw characteristics

Perioperative variables	All	No breach	Breach	P value
Total number of screws	65	61	4	–
Mean length of screw ± SD	84.6±6.1	84.4±6.2	87.5±5.0	0.336
Mean diameter of screw ± SD	8.4±0.7	8.4±0.7	8.9±0.5	0.155
Mean axial angle ± SD	49.6±5.6	49.3±5.7	53.5±4.6	0.160
Mean sagittal angle ± SD	24.0±10.5	24.3±10.1	19.7±17.8	0.403

SD, standard deviation.

Table 3 Screw breach characteristics

Characteristics	Value
Total number of screws	65
Total breaches	4 (6.3%)
Average breach distance (mm)	3.5±3.2
Breach grade	
A (0 mm, no breach)	61 (93.8%)
B (<2 mm)	3 (4.6%)
C (<4 mm)	0
D (<6 mm)	0
E (>6 mm)	1 (1.5%)
Direction of breach	
Anterior	3 (4.6%)
Posterior	0
Inferior	1 (1.5%)
Exchange of S2AI screw for breach	1 (1.5%)
Postoperative neurologic complications	0

to the hospital. One patient was readmitted for pre-existing medical issues and not due to his spinal surgery. Another patient who underwent a T3 to pelvis fusion suffered a ground level fall 2 weeks after surgery and was found to have a proximal junctional kyphosis which was appropriately revised. After thorough chart review, no postoperative and post-discharge wound complications related to the S2AI screw, screw prominence issues, or revision of S2AI screws were observed during the study's follow-up period.

Discussion

Over the last two decades, robot-assisted spine surgery has become increasingly common (16-19). This is largely attributed to the plethora of literature validating the high precision and accuracy of robot-assisted pedicle screw placement (19-22). Recently, a few studies have emerged demonstrating the feasibility of the technology for S2AI screw placement; however, this literature remains relatively sparse and limited to single-center studies.

In 2017, Bederman *et al.* introduced the first study to report on the accuracy of robot-assisted S2AI screws. They used the SpineAssist/Renaissance surgical robot on fourteen patients (31 S2AI screws) at a single institution and reported that all screws were acceptable without any proximal breach into the anterior sacrum. Ten screws protruded the ilium distally by ≥4 mm, but these screws were deemed to be not at risk for injuring visceral or neurovascular structures and were not revised. These authors found that longer screws (≥80 mm) appeared to be more likely associated to distal protrusion than shorter screws. Although these initial results were encouraging, the authors acknowledge significant limitations. First, the preoperative CT scan included only lumbosacral views (and not the pelvis). Therefore, only a limited view of the pelvis was available during preoperative planning and often the most distal aspect of the screw trajectory could not be adequately planned. Furthermore, the robotic planning software used was only able to account for up to 60 mm of screw trajectory, even though screw lengths of 65 to 90 mm were used (23). The manual guidance required due to these limitations is likely what contributed to the poor distal accuracy of these screws.

In another small retrospective study, Hu *et al.* examined 35 robot-assisted S2AI screws in eighteen patients by comparing the pre- and postoperative CT scans. They reported that there was no screw malposition, including any breach to the anterior sacrum or iliac cortex, and no screw-related complications. By superimposing the pre- and postoperative CT scans, they reported that the screw

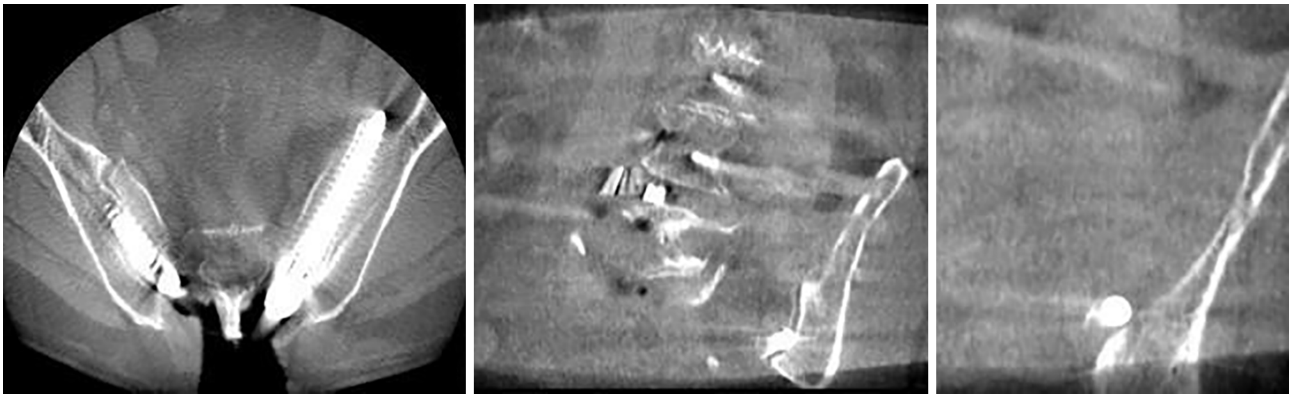

Figure 2 An example of an anterior screw breach through the iliac cortex. From left to right, the axial image demonstrates the anterior cortical breach, the middle photo shows how the screw deviation into the SI joint likely contributed to the screw breach, and the tear drop view demonstrates the degree of cortical breach.

Figure 3 An illustrative case of a patient who underwent a T10 to pelvis fusion for degenerative lumbar scoliosis. From left to right, the preoperative posterior-anterior, preoperative lateral, postoperative posterior-anterior, and postoperative lateral standing radiographs are shown. Bilateral S2AI screws were placed without breach or complication. The scoliotic deformity was corrected and the lumbar lordosis was restored. S2AI, S2 alar-iliac.

deviated by 3.0±2.2 mm in the axial plane and 1.8±1.6 mm in the sagittal plane. However, no data was presented regarding the screw lengths, diameter, or trajectory used, and the radiographic measurements were manually performed by a single observer (24).

Recently, Laratta *et al.* evaluated 46 robot-assisted S2AI screws in 23 patients. The overall screw accuracy was 95.7% (two breaches: one posterior and one anterior) with a mean breach distance of 7.9±4.8 mm. In comparison to prior studies, all patients had complete O-arm/CT imaging of the pelvis which was analyzed using three-dimensional CT-based software (Vitrea Core) to more reliably and accurately characterize the screw trajectory and breach. Interestingly, they were not able to detect a statistical difference in mean angles (both in the axial and sagittal planes) between those with and without a cortical breach. No intraoperative neurologic, vascular, or visceral complications were observed in this study; however, potential post-discharge complications were not assessed (14).

Shillingford *et al.* performed the first propensity-matched analysis of the accuracy of freehand (59 screws) versus robot-assisted (46 screws) S2AI screws. No statistical difference in screw accuracy was observed (Freehand: 94.9% *vs.* Robot: 97.8%, P=0.630). The mean breach distance was similar as well (Freehand: 3.9±2.2 mm *vs.* Robot: 7.9±4.8 mm, P=0.160). No intraoperative neurovascular or visceral complications were observed in either cohort. Of note, the freehand cohort was performed by a single experienced senior surgeon. These authors acknowledged that a learning curve exists for both freehand and robot-assisted screws, and this was not objectively controlled for in their study (25).

There are a number of differences between our study and those previously reported. First, our study provides the largest assessment of S2AI screws to date, and is the first non-single center study on this topic which can control for the potential variability that may exist among different surgeons and institutions. Second, no prior study has investigated S2AI screws for the Mazor X robot, which is a relatively new system, since all prior studies have used the Renaissance robot. As new robot technology continues to be introduced into practice, it is important for the surgeon to know how these new advances are influencing screw accuracy and outcomes. In our study, the overall screw accuracy was 93.8% (no breach) and the acceptable screw rate (no screw exchange) was 98.5%, which is consistent with the high accuracy rates reported in literature. Similar to Laratta *et al.*, we used the Vitrea Core software to obtain hi-fidelity screw measurement data but we were not able to determine a statistically significant difference in screw length, diameter, axial angle, or sagittal angle between screws with and without a breach. Since only four screw breaches occurred, we were not powered to perform a multivariate risk factor analysis. In a secondary analysis for these four patients, we found that obesity was significantly associated with screw breach based on bivariate chi-square results [no breach: 25% (n=1) *vs.* breach: 75% (n=3), P=0.043]. Other factors such as age, smoking, osteoporosis, revision surgery and preoperative diagnosis did not show statistically significant associations. However, it is likely that the breach occurrence was too low to discern a statistically significant difference. A potential explanation for the screw breaches that we empirically observed is surgical tool skiving and inadequate exposure of soft tissues introducing translational force to instruments as they are placed. The tines on the end of the drill guide help minimize this error, but further efforts to improve surgical exposure for better visualization and prepare the anatomical landing area especially for abnormal or uneven bony surfaces may help circumvent this. Nevertheless, these cortical breaches did not result in any clinically significant complications. Finally, we performed a chart review for both intraoperative and postoperative/post-discharge complications, and we determined that no S2AI-related complications were observed during this study's follow-up period.

Other limitations to this study include the relatively short minimum follow-up period. Although the mean follow-up of our study was nearly one year, it is possible that S2AI complications can occur well-beyond this follow-up period, such as screw migration for breached screws. We acknowledge the relatively small sample size in comparison to larger multicenter studies. Our priority was to study a relatively uniform sample of patients between institutions to control for the confounding effects of robot type and screw measurement error. This meant the inclusion of only one type of robot system and those who had an intraoperative O-arm CT scan to enable Vitrea Core analysis. Unfortunately, this came at the cost of fewer patients. Future studies should perform comparative analyses between robot systems, multicenter analyses with a freehand cohort, assess the influence of robot-assistance on operative work flow and cost efficiency, as well as radiation exposure.

Conclusions

Despite these limitations, this is the first study involving more than one hospital center to confirm the high accuracy, reliability, and safety of robot-assisted S2AI screw fixation. The overall screw accuracy was 93.8% (no breach) and the acceptable screw rate (no screw exchange) was 98.5%. No intraoperative or post-discharge complications directly related to S2AI screws were observed during this study's follow-up period. Another important benefit to emphasize is the new robotic guidance software which allows for detailed and precise preoperative and intraoperative planning. Using the software's three-dimensional analytics, surgeons are able to customize implant size, diameter and fine-tune each screw trajectory in all three planes. In addition, one can see the interbody cages in 1:1 size with a 3D rendering. Furthermore, the X Align software allows for the performance of osteotomies, enables surgeons to classify the curves according to the Lenke Classification for adolescent idiopathic scoliosis and the SRS classification for adult deformity. This is particularly useful for S2AI fixation since surgeons can plan for a mechanically sound construct and easy passage of the rod to connect harmoniously with S2AI fixation, without the need for connectors.

Acknowledgments

Funding: None.

Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://dx.doi.org/10.21037/jss-21-14

Data Sharing Statement: Available at https://dx.doi.org/10.21037/jss-21-14

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://dx.doi.org/10.21037/jss-21-14). JPM reports grants from AO Spine and Medtronic, outside submitted work. JP reports other from Medtronic, other from ATEC Spine, outside the submitted work. RAL reports consultant/royalty fees from Medtronic, royalty fees from Stryker, research grants from the Department of Defense, outside the submitted work. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by ethics board of Columbia University and State University of New York (AAAT1470) and individual consent for this retrospective analysis was waived.

References

1. Galbusera F, Casaroli G, Chande R, et al. Biomechanics of sacropelvic fixation: a comprehensive finite element comparison of three techniques. Eur Spine J 2020;29:295-305.
2. Casaroli G, Galbusera F, Chande R, et al. Evaluation of iliac screw, S2 alar-iliac screw and laterally placed triangular titanium implants for sacropelvic fixation in combination with posterior lumbar instrumentation: a finite element study. Eur Spine J 2019;28:1724-32.
3. Kebaish KM. Sacropelvic fixation: techniques and complications. Spine (Phila Pa 1976) 2010;35:2245-51.
4. Shin JK, Lim BY, Goh TS, et al. Effect of the screw type (S2-alar-iliac and iliac), screw length, and screw head angle on the risk of screw and adjacent bone failures after a spinopelvic fixation technique: A finite element analysis. PLoS One 2018;13:e0201801.
5. Shaffrey CI, Smith JS. Stabilization of the sacroiliac joint. Neurosurg Focus 2013;35:Editorial.
6. O'Brien JR, Yu W, Kaufman BE, et al. Biomechanical evaluation of S2 alar-iliac screws: effect of length and quad-cortical purchase as compared with iliac fixation. Spine (Phila Pa 1976) 2013;38:E1250-5.
7. Hasan MY, Liu G, Wong HK, et al. Postoperative complications of S2AI versus iliac screw in spinopelvic fixation: a meta-analysis and recent trends review. Spine J 2020;20:964-72.
8. De la Garza Ramos R, Nakhla J, Sciubba DM, et al. Iliac screw versus S2 alar-iliac screw fixation in adults: a meta-analysis. J Neurosurg Spine 2018;30:253-8.

9. Mastrangelo G, Fedeli U, Fadda E, et al. Increased cancer risk among surgeons in an orthopaedic hospital. Occup Med (Lond) 2005;55:498-500.
10. Hyun SJ, Kim KJ, Jahng TA, et al. Efficiency of lead aprons in blocking radiation - how protective are they? Heliyon 2016;2:e00117.
11. Hyun SJ, Kim KJ, Jahng TA, et al. Minimally Invasive Robotic Versus Open Fluoroscopic-guided Spinal Instrumented Fusions: A Randomized Controlled Trial. Spine (Phila Pa 1976) 2017;42:353-8.
12. Marintschev I, Gras F, Klos K, et al. Navigation of vertebro-pelvic fixations based on CT-fluoro matching. Eur Spine J 2010;19:1921-7.
13. Jiang B, Azad TD, Cottrill E, et al. New spinal robotic technologies. Front Med 2019;13:723-9.
14. Laratta JL, Shillingford JN, Lombardi JM, et al. Accuracy of S2 Alar-Iliac Screw Placement Under Robotic Guidance. Spine Deform 2018;6:130-6.
15. Gertzbein SD, Robbins SE. Accuracy of pedicular screw placement in vivo. Spine (Phila Pa 1976) 1990;15:11-4.
16. D'Souza M, Gendreau J, Feng A, et al. Robotic-Assisted Spine Surgery: History, Efficacy, Cost, And Future Trends. Robot Surg 2019;6:9-23.
17. Joseph JR, Smith BW, Liu X, et al. Current applications of robotics in spine surgery: a systematic review of the literature. Neurosurg Focus 2017;42:E2.
18. Overley SC, Cho SK, Mehta AI, et al. Navigation and Robotics in Spinal Surgery: Where Are We Now? Neurosurgery 2017;80:S86-99.
19. Fiani B, Quadri SA, Farooqui M, et al. Impact of robot-assisted spine surgery on health care quality and neurosurgical economics: A systemic review. Neurosurg Rev 2020;43:17-25.
20. Devito DP, Kaplan L, Dietl R, et al. Clinical acceptance and accuracy assessment of spinal implants guided with SpineAssist surgical robot: retrospective study. Spine (Phila Pa 1976) 2010;35:2109-15.
21. Molliqaj G, Schatlo B, Alaid A, et al. Accuracy of robot-guided versus freehand fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery. Neurosurg Focus 2017;42:E14.
22. Fan Y, Peng Du J, Liu JJ, et al. Radiological and clinical differences among three assisted technologies in pedicle screw fixation of adult degenerative scoliosis. Sci Rep 2018;8:890.
23. Bederman SS, Hahn P, Colin V, et al. Robotic Guidance for S2-Alar-Iliac Screws in Spinal Deformity Correction. Clin Spine Surg 2017;30:E49-53.
24. Hu X, Lieberman IH. Robotic-guided sacro-pelvic fixation using S2 alar-iliac screws: feasibility and accuracy. Eur Spine J 2017;26:720-5.
25. Shillingford JN, Laratta JL, Park PJ, et al. Human versus Robot: A Propensity-Matched Analysis of the Accuracy of Free Hand versus Robotic Guidance for Placement of S2 Alar-Iliac (S2AI) Screws. Spine (Phila Pa 1976) 2018;43:E1297-304.

Cite this article as: Lee NJ, Khan A, Lombardi JM, Boddapati V, Park PJ, Mathew J, Leung E, Mullin JP, Pollina J, Lehman RA. The accuracy of robot-assisted S2 alar-iliac screw placement at two different healthcare centers. J Spine Surg 2021;7(3):326-334. doi: 10.21037/jss-21-14