Tai Chi (太極) Pedicle Screw Placement for Severe Scoliosis

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Study Design: Retrospective.

Objective: To evaluate the clinical safety and accuracy of the Tai Chi (太極) technique for placing pedicle screws, without intraoperative radiographic imaging, in severe scoliotic spines.

Summary of Background Data: The current techniques for pedicle screw placement have a number of drawbacks in cases of severe scoliosis, including difficulty or impossibility to use, delayed operative time, requiring the presence of trained personnel for the duration of the surgery, high cost issues, increased radiation exposure, and technical challenges. No previous report has described the application of the Tai Chi pedicle screw placement technique for severe scoliosis.

Material and Methods: Between 2006 and 2008, the cases of 39 consecutive patients with severe scoliosis (Cobb angle >100 degrees) who underwent posterior correction and stabilization (from T1 to L5) using 992 transpedicular screws were examined. The mean patient age was 25.7 (range, 11 to 63) years at the time of surgery. Pedicle screws were inserted by the Tai Chi technique using anatomic landmarks and preoperative radiographs as a guide. Tai Chi drilling fully utilizes the natural anatomic and physical characteristics of pedicles and unconstrained circular force. By nature, a drill bit driven by unconstrained circular force would migrate within the pedicle along a path of least resistance, advancing along the central cancellous bone tunnel spontaneously. Accurate drilling was achieved by following the nature and sticking to the hand sensation when the drill bit broke through the cancellous bone. The total time for inserting all pedicle screws in each case was recorded. Postoperative computed tomography scans were performed to evaluate the position of the inserted pedicle screws. The screw position was classified as "in" or "out." The distance of perforation was measured.

Result: The average Cobb angle was 127 degrees (range, 100 to 153 degrees). The number of screws inserted at each level were as follows: T_1 (n = 10), T_2 (n = 34), T_3 (n = 46), T_4 (n = 53), T_5 (n = 61), T_6 (n = 69), T_7 (n = 75), T_8 (n = 76), T_9 (n = 76), T_{10} (n = 77), T_{11} (n = 76), T_{12} (n = 78), L_1 (n = 77), L_2 (n = 68), L_3 (n = 56), L_4 (n = 38), and L_5 (n = 22). There were 923 (93%) "in" screws and 69 (7%) "out" screws. The overall accuracy of screw placement was 93%. There were no neurological, vascular, or visceral complications. No screws required postoperative repositioning. The average time for pedicle screw placement was 73 seconds.

Conclusions: Our findings suggest that the Tai Chi pedicle screw placement technique, which does not require intraoperative radiographic imaging, is an accurate, reliable, safe, and time-saving method of placing pedicle screws in severe scoliotic spines.

Key Words: accuracy, pedicle screw placement, severe scoliosis, Tai Chi

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Severe scoliotic deformities require multiple stable and strong anchorages to facilitate the forces necessary for initial and maintained correction and rigid fixation. Pedicle screws allow for optimal attachment to the spine. However, the placement of a pedicle screw in severe scoliotic spines is a technically demanding procedure that has the potential for significant neurological, vascular, and visceral injury.

A variety of different techniques are currently used for the placement of pedicle screws. These techniques include the use of anatomic landmarks, laminotomy with palpation of the pedicle, C-arm fluoroscopy, computer-assisted techniques, and freehand techniques.[1–8] In addition, electrophysiological monitoring or electrical stimulation techniques can be used in combination with these methods.[9,10] Different approaches have recently been described for pedicle screw insertion with good laboratory[11,12] and early clinical findings.[4–7] New and expensive technology, such as 3-dimensional computer-assisted surgery and computer-assisted fluoroscopy, are associated with high doses of radiation and increased procedural times, and are not widely available.[13] However, the practical application of these techniques/approaches has not been examined with reference to the treatment of severe scoliosis.

One of the authors of this manuscript (also a senior surgeon who has inserted over 50,000 pedicle screws) has developed a Tai Chi (太極) technique to place pedicle screws in severely scoliotic spines without the use of intra-operative fluoroscopy, radiography, or neurophysiologic

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monitoring. In the present study, we aimed to evaluate the safety and accuracy of the Tai Chi technique for placing pedicle screws in severe scoliotic spines.

MATERIALS AND METHODS

Patients and Measures

The records of 39 consecutive patients with severe scoliosis (Cobb angle ≥ 100 degrees) who underwent posterior correction and fixation from 2006 to 2008 were examined. All procedures were performed by a single senior surgeon with the assistance of at least 1 orthopedic specialist registrar. Drilling and screw placement were carried out by the senior surgeon.

All pedicle screws were inserted using the Tai Chi technique. An independent spinal surgeon retrospectively reviewed the medical records and postoperative roentgenograms of all patients to assess the screw-related neurological, vascular, and visceral complications.

To objectively evaluate the position of the screws inserted into the severely scoliotic spines, postoperative computed tomography (CT) scans and sagittal and coronal reconstructions were performed for all patients. The transverse images were examined by an independent radiologist who classified the screws as being "in" or "out" (Fig. 1). A screw was classified as "in" if the central line of the screw was inside the outer cortex of the pedicle wall. A screw was classified as "out" if the central line of the screw was outside the outer cortex of the pedicle wall. The distance of perforations was measured.[4]

Surgical Technique

Pedicle screws were placed with reference to anatomic landmarks as guided by preoperative antero-posterior/lateral radiographs and CT scans. The starting point for the 12th thoracic vertebra and lumbar vertebrae pedicle screw insertion was the junction of the bisected transverse process and lateral border of the superior articular process. The starting point for T1 to T11 pedicle screw insertion was the junction of the proximal edge of the transverse process and the lateral border of the superior articular process. The surgeon stood by the concave side of the scoliosis to insert convex and concave pedicle screws and moved to the other side to insert pedicle screws in cases of double curves.

The surgeon stood firmly on the ground, concentrating and focusing all his attention on the surgery at hand. A power drill loaded with a 3.2-mm drill bit was held (the hand piece of the power drill should be as light as possible to maximize hand sensitivity) and a laser mark was made 35 mm from the tip of the drill bit to serve as a reference point during the advancement of the drill bit within the pedicle. We used a drill bit that was 3.2 mm in diameter because the continuous feedback signal from the drill bit could be easily sensed by hand. A rougeur was used to expose the cancellous bone of the starting point. The tip of the drill bit was placed into the cancellous bone of the starting point. The approximate orientation of the drilling trajectory was determined with reference to preoperative images. The pedicle consists of an outer hard cortical wall and a central soft cancellous bone, which can be considered as a natural tunnel to the vertebral body. Power drilling causes the drill bit to move in a circular motion. The circular motion of the drill bit caused a reaction force by ejecting the cancellous bone chips along the drill flute backward. The reaction force acted on the floor of the flute and aided the ventral migration of the drill bit within the pedicle (self-generated migration force) (Fig. 2). The resistance to penetration is quite different between a central soft cancellous bone and the cortical wall of the pedicle. By adjusting the magnitude of external ventral pressure by the operator in addition to the weight of the drill hand piece and the self-generated migration force, the resultant force of ventral migration could be controlled easily to advance the drill bit within the cancellous bone tunnel without penetrating the cortical wall of the tunnel. As the action of exerting ventral pressure on the drill can fix the trajectory of drilling, the surgeon released the ventral pressure from time to time, held the hand piece loosely, and relaxed his wrist so as to let the weight of the drill hand piece and the self-generated migration force guide the drill bit. The unconstrained drill bit hence migrated within the pedicle along a path of least resistance,

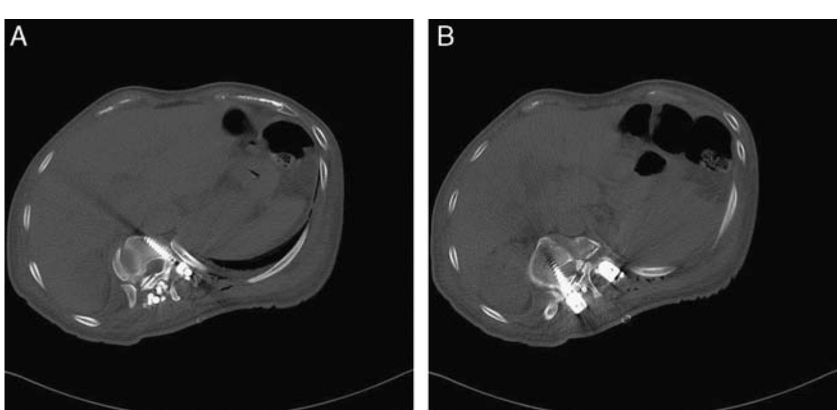

FIGURE 1. Pedicle screws were classified as (A) "in" or (B) "out."

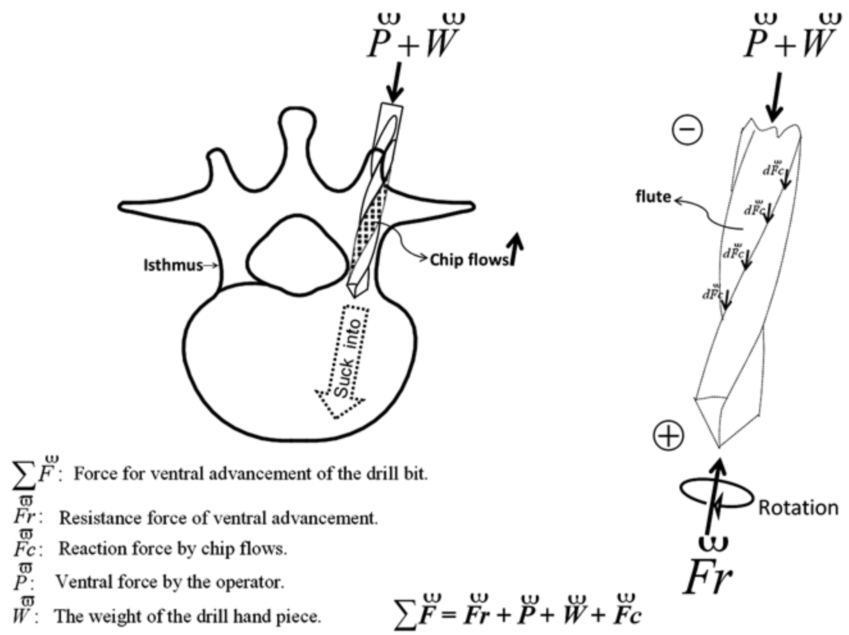

FIGURE 2. Physical analysis of the "suck into" phenomenon. The force for ventral advancement of a drill bit within a pedicle is the resultant force of the resistance force of ventral advancement (Fr), the external ventral pressure by the operator (P), the weight of the drill hand piece (W), and the reaction force (Fc) acting on the floor of the drill flute, which is generated by the circular motion of the drill bit. Ventral advancement of a drill bit produces cancellous bone chips. The narrow inner cancellous canal of the isthmus provides an environment wherein cancellous bone chips can easilystagnate in the flute. The circular motion of the drill bit causes dorsal pressure on the stagnant bone chips to eject them along the flute backward and generates a greater Fc for ventral advancement of the drill. The greater Fc adds to P and W to overcome the increased resistance (Fr) of ventral advancement of the drill at the narrow isthmus of a pedicle. After the tip of the drill bit has passed through the isthmus, Fr decreases. However, the increased Fc persists because the flute with the stagnation is still within the isthmus. When the increased Fc is large enough to play the role of P in ventral advancement of the drill, the operator feels through hand that the external ventral pressure is no longer necessary and the drill seems to be sucked into the vertebral body. The appearance of the "suck into" phenomenon in the presence of hand sensation of the drill bit breaking through the specific resistance imparted by cancellous bone requires the drill bit to be accurately passed through the narrow isthmus into the vertebral body, which means that the drilling path is accurate.

advancing along the cancellous bone tunnel spontaneously. During the aforementioned process, the surgeon should focus on the feel of the drill bit (sensed through the hand holding the drill) breaking through the specific resistance of the central cancellous bone while advancing ventrally. The drilling motion and trajectory are adjusted with reference to the feedback/sensation obtained by holding the drill (drilling motion sticks to the sensation change). This is the first phase of the Tai Chi drilling.

The surgeon should pay particular attention to the junction of the middle and upper portions of the tunnel (the first 10 to 15 mm of the tunnel), as this is the region of the pedicle where the spinal canal and pedicle isthmus are located. For pedicles or pedicle regions (such as the isthmus) with a narrow endosteal diameter, the ventral force may be insufficient to further advance the drill bit. Hence, additional ventral pressure by the operator may have to be applied to overcome the increased resistance of migration in the narrow portion of the pedicle. Slowly advancing the drill bit (assessed by closely monitoring advancement of the laser mark on the drill bit) and focusing on the sensation of the drill are the 2 main indicators of accurate drilling through the central cancellous bone of the pedicle at this region (Table 1). A sensation of increased resistance to advancement of the drill bit in combination with slow ventral advancement indicates accurate drilling in this region. The handpiece of the drill was gently rolled clockwise frequently while drilling, allowing the tip of drill bit to fall into the tunnel, thus promoting accurate drilling. Any sudden advancement of the drill bit suggests that penetration of the pedicle wall may have occurred. In such cases, the pedicle should be abandoned to avoid complications. This is the second phase of Tai Chi drilling.

After the drill tip had passed through the isthmus of the pedicle, resistance decreased and faster ventral advancement occurred. Very often a specific physical phenomenon (named "suck into" phenomenon) would appear immediately after the tip of the drill bit had passed through the isthmus (Fig. 2). At this point, the resistance decreased, the self-generated migration force increased[14] and it played the role of the ventral pressure by the operator in ventral advancement of the drill. The operator could sense through the hand that the external ventral pressure was not necessary any longer and the drill seemed to be sucked into the vertebral body. The

TABLE 1. Status of 2 Sensory Indicators at Different Regions of a Pedicle While Drilling

	Region of Pedicle				
Sensory Indicator	**Initial Pedicle Tunnel**	**Pedicle Isthmus**	**Pedicle Wall**	**Vertebral Body**	**Penetration Into Soft Tissue**
Resistance of advancement (sensed by hand)	+ +	+ + +	+ + + +	+ +	−
Speed of advancement (sensed by vision)	+ +	+	−	+ +	+ + + +

appearance of this specific physical phenomenon in the presence of sensation of the drill bit breaking through the specific resistance imparted by cancellous bone is a strong indicator of accurate drilling. Drilling proceeded until the laser mark reached the bone. This is the third phase of Tai Chi drilling. After this, the tunnel was palpated using a flexible ball-tipped probe to confirm the presence of circumferential bone. If a soft tissue breach was palpated, bone wax was inserted to stem the bleeding and the pedicle was abandoned.

Screws were inserted relatively easily and were not forced. Titanium screws of varying diameters (7.0, 6.5, 6.0, 5.5, or 5.0 mm) were used depending on the vertebral level, the size of the patient, tightness while screwing, and preoperative radiographic assessment. It is advantageous to work from distal to proximal and bilaterally (the surgeon stood on the concave side and inserted both convex and concave side pedicle screws level by level) in succession and to make fine adjustments to the trajectory of the next screw on the basis of the previous level and contralateral screws. No fluoroscopy, x-rays, or neurophysiological study was performed during surgery. The total time taken to insert all pedicle screws in each case was recorded. After the insertion of the pedicle screws, deformity correction and stabilization were carried out using the cantilever bending technique (Figs. 3, 4).[15]

RESULTS

A total of 39 patients with severe scoliosis who had a mean age of 25.7 years (range, 11 to 63 y) were included in the study. A total of 992 pedicle screws were placed from T1 to L5 and evaluated for the placement accuracy. The placement of 32 pedicle screws had to be abandoned because of intraoperative penetration of the pedicle wall. The placement of 3 pedicle screws had to be abandoned because of a soft tissue breach (palpated after drilling). These abandoned pedicles did not affect the deformity correction or the fixation because pedicle screws were successfully inserted in the adjacent pedicles. The average

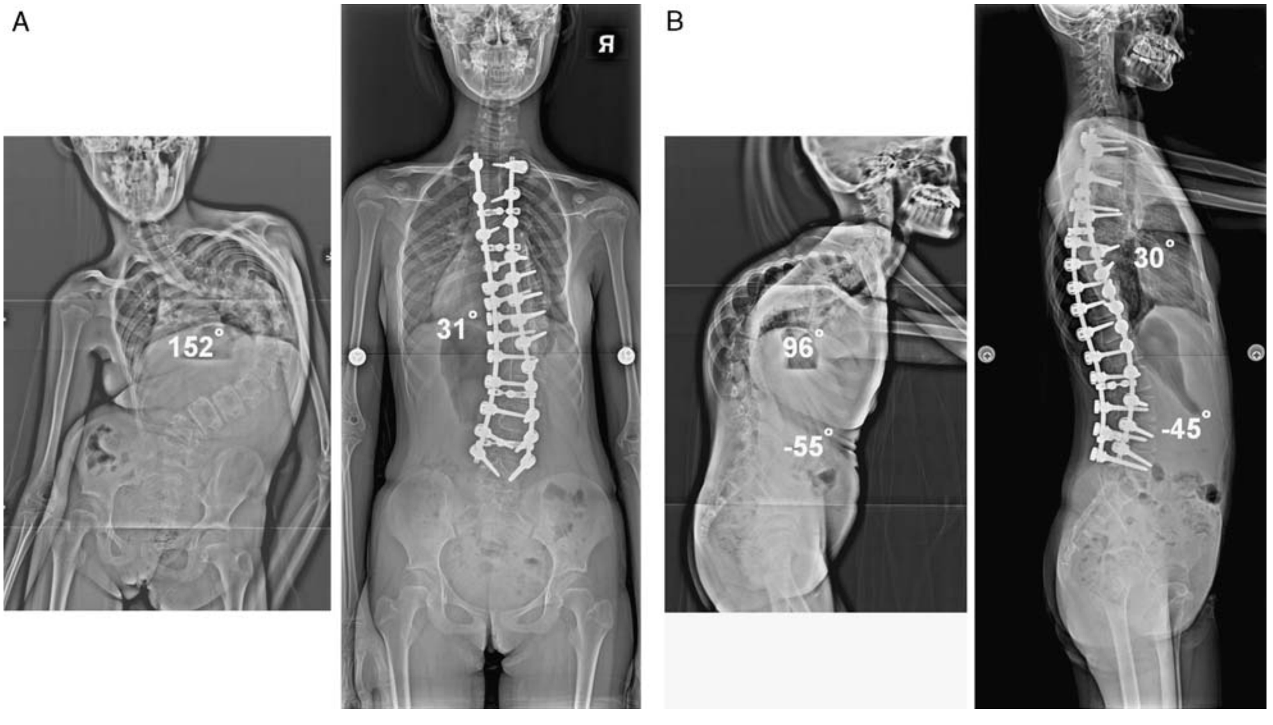

FIGURE 3. A and B, An illustrative case of a patient with severe scoliosis (Cobb angle = 152 degrees) who was treated using the Tai Chi pedicle screw placement technique and the cantilever bending technique. Each pedicle screw was accurately inserted to obtain multiple strong anchors so that powerful corrective forces could be provided to overcome the rigidity of the deformity and facilitate satisfactory correction without the need for anterior release procedures.

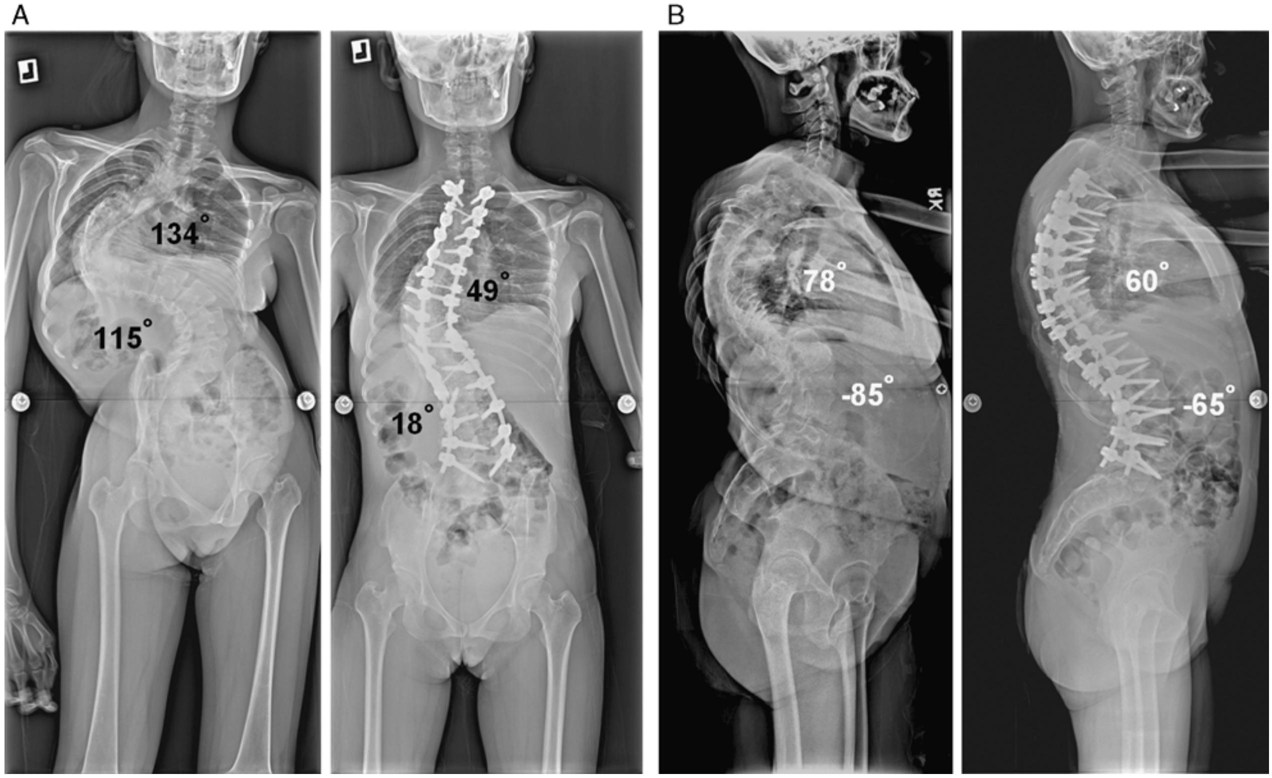

FIGURE 4. A and B, An illustrative case of a patient with a severe double major curve (Cobb angles of 134 and 115 degrees) who was treated using the Tai Chi pedicle screw placement technique and the cantilever bending technique. Each pedicle screw was accurately inserted to provide powerful corrective forces and facilitates satisfactory correction without the need for anterior release procedures.

length of follow-up was 33.4 months (range, 24 to 48 mo). The etiologic diagnoses of scoliosis were as follows: adolescent idiopathic scoliosis (n = 13), congenital scoliosis (n = 5), neurofibromatosis (n = 4), adult idiopathic scoliosis (n = 11), Marfan syndrome (n = 4), and neuromuscular scoliosis (n = 2). The average Cobb angle of scoliosis was 127 degrees (range, 100 to 153 degrees).

The distribution of the pedicle screws per level and the corresponding accuracy of placement can be seen in Table 2. A total of 885 of 992 screws were placed correctly (93%), whereas 33 of the 69 (7%) screws classified as "out" had medial penetrations. The average pedicle breach for "out" screws was 2.3 mm (range, 1.5 to 4.7 mm). The average medial encroachment was 1.7 mm (range, 0.3 to 3.3 mm).

The total time taken to place the 992 pedicle screws was 1206 minutes and 55 seconds. Hence, the average time taken for the placement of each pedicle screw was 73 seconds.

Complications

There were no postoperative neurological or vascular complications. At the latest follow-up, there were no late-onset neurological complications. There were 5 instances of cerebrospinal fluid leakage from the initial pedicle tract because of the penetration of the medial wall. In each instance, the tract was sealed using bone wax and the pedicle was abandoned. There were no postoperative cerebrospinal fluid leaks.

DISCUSSION

Treatment of severe scoliosis requires the insertion of multiple strong anchors to provide the powerful corrective forces needed to overcome the rigidity of the deformity and facilitate satisfactory correction without the need for anterior release procedures.[15] Pedicle screws have proved to be superior to all other posterior fixation devices for such anchorage.[16] However, because of the complex 3-dimensional deformity of the spinal column and the pedicles located on the concave side of the severely scoliotic spine,[17] insertion of pedicle screws remains technically challenging.

Because of the proximity of vital neurological, vascular, and visceral structures, the misplacement of spinal screws can lead to complications.[18–20] Misplaced pedicle screws also have a biomechanical disadvantage. The pull-out strength and the rotational stability are maximized if the major screw diameter fills more than 70% of the pedicle diameter, and also if the screws are medially angled and deeply inserted into the vertebral body.[21–24]

TABLE 2. Screw Placement Distributions and Accuracy

Levels	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5	Total
No. screws	10	34	46	53	61	69	75	76	76	77	76	78	77	68	56	38	22	992
Out	1	3	2	4	3	13	9	7	8	7	4	5	2	1	0	0	0	69
Accuracy (%)	90	91	96	92	95	81	88	91	89	91	95	94	97	99	100	100	100	93

L indicates lumbar; T, thoracic.

There are many methods available to aid surgeons in the safe placement of pedicle screws.[1–12,25,26] However, these techniques have a number of drawbacks in cases of severe scoliosis including difficulty or impossibility to use, delayed operative time, requiring the presence of trained personnel for the duration of the surgery, high cost issues, increased radiation exposure, and technical challenge.[25–29]

To our knowledge, we have reported the largest number of pedicle screws placed in severely scoliotic spines without the assistance of x-ray, fluoroscopy, navigation, or neurophysiological study during surgery. Simple anatomic landmarks were used. The overall accuracy of 93% compares well with the aforementioned studies reporting on pedicle screw placement.[1–12] It should be noted, however, that those reports include some nondeformity cases in the final statistic. Safeguards of the Tai Chi pedicle screw placement technique included the drilling motion sticking to the hand sensation of the drill bit breaking through the specific resistance of the central cancellous bone while advancing ventrally, drilling guided by 2 sensory indicators of resistance and speed of advancement during drilling, and abandonment of the pedicle upon penetration of the pedicle wall during drilling and if the circumferential bone was palpated after drilling. In this study, the average time taken to place 1 pedicle screw was 73 seconds. We believe that the Tai Chi technique is the optimal time-saving technique for placing pedicle screws in cases of severe scoliosis and so to preserve surgeons' energy and prevent exhaustion.

A total of 69 of 992 (7%) screws were classified as "out" screws according to postoperative CT scans. The probable causes of these inaccurate placements include the following: (1) the insertion of excessively wide screws[4,30,31]; (2) differences between the drilling and screwing trajectories[32]; (3) a diagonal drilling tract within a pedicle[27]; (4) or an inaccurate drilling trajectory and poor application of the 4 aforementioned safeguards. (1), (2), and (3) are the probable causes of inaccurate placement in this study. However, we do not believe that any instances where the drilling trajectory was inaccurate in our series were due to a lack of application of the procedural safeguards. Unacceptable medial or lateral pedicle breach may occur and result in serious complications. We have not experienced any complications from such medial or lateral pedicle breaches at this time.

The acceptable degree of medial and lateral pedicle breach remains controversial and is therefore a suboptimal means for evaluating screw safety.[18,19,33,34] The acceptable limits of screw penetration are even less clear in patients with spinal curvatures, where the thecal sac is shifted toward the concave side.[20] Clinically, encroachment of the epidural space up to 2 mm is conservatively considered to be safe in most cases.[32–35] Although a total of 26 of the 69 "out" screws resulted in a pedicle breach > 2 mm, none of these misplaced screws resulted in injury.

Why is this technique named Tai Chi? Tai Chi is a part of traditional Chinese culture. It is an internal, ancient martial art and exercise based on the ancient Chinese Tao philosophy. Tai Chi helps the practitioner to become physically fit and mentally relaxed, and promotes inward focus, alertness, and reactivity. Tai Chi exercise trains both the body and the mind, improving harmony between the 2. The main concept of Tai Chi is to focus on slow, soft circular movement. The motion neither goes too far nor falls short. When the opponent is hard, I am soft. When the opponent is soft, I follow. To the opponent's fast movement, I react fast. To the opponent's slow movement, I react slowly. Change is innumerable, but the principle is always the same (this is called sticking). Tai Chi force is generated from a circular motion. Power drilling also generates a circular motion in the drill bit. Hand sensation is critically important for the successful insertion of pedicle screws using the Tai Chi pedicle screw placement technique. Hand control and fine adjustment of drill motion and trajectory should be closely dictated by sensation. We suggest that surgeons should memorize and become familiar with specific hand sensations in nondeformity or mild deformity cases, and then later, cases of severe scoliosis. Ultimately, satisfactory hand control and fine adjustment of the drilling motion and trajectory will be harmonized in response to hand sensation. Instant and proper control of the drilling motion will accurately follow the specific hand sensation (this is sticking). Gradually, screw placement in severe scoliosis would constitute no major difficulty. Because this technique has all the important characteristics of Tai Chi, we named it the Tai Chi technique. However, it is not necessary to learn Tai Chi to have this technique be validated by surgeons. Most surgeons are fully capable of using this technique.

Studies have demonstrated that there is a high prevalence of screw misplacement associated with drilling[35] compared with blunt screw application.[36] Hence, most surgeons believe drilling the path for pedicle screw placement is dangerous and adopts a blunt technique with an awl or a gearshift for pedicle screws placement. However, our experience is different. In this study, we found that Tai Chi drilling for pedicle screw placement fully utilizes the natural anatomic and physical characteristics

TABLE 3. Comparison Between the Tai Chi Technique and Other Freehand Techniques

Tai Chi Technique	Freehand Techniques
Force for ventral migration of the drill bit provided by electric power could be unconstrained and would not fix the drilling trajectory	Force for ventral migration of an awl or a gearshift provided by hand would be constrained and fix the awl's or gearshift's trajectory
Circular motion of a drill bit by drilling overcomes resistance with soft solution	Straight motion of an awl or a gearshift by hand overcomes resistance with hard solution
A drill bit driven by unconstrained circular force would migrate along a path of least resistance and advance along the cancellous bone tunnel spontaneously	An awl or a gearshift driven by constrained straight force funnels the cancellous bone tunnel by careful hand control
Fully utilize the natural anatomic and physical characteristics of pedicles and unconstrained circular force	None
Explicable by physical analysis	None

of pedicles and unconstrained circular force. By nature, a drill bit driven by unconstrained circular force would migrate within the pedicle along a path of least resistance, advancing along the central cancellous bone tunnel spontaneously. Following the nature and with the aid of the sticking technique, surgeons can place pedicle screws accurately. The technique can also be clearly described and is explicable by physics (Table 3). It was demonstrated to be accurate, reliable, safe, and time saving, provided special attention is paid to preoperative images and the described insertion technique.

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