Monitoring the Quality of Robot-Assisted Pedicle Screw Fixation in the Lumbar Spine by Using a Cumulative Summation Test

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Study Design. Prospective randomized controlled trial.
Objective. The aim of this study was to monitor the quality control of robot-assisted pedicle screw fixation accuracy by using a cumulative summation (CUSUM) test at the initial stage of its application.

Summary of Background Data. Although robot-assisted pedicle screw fixation reduces screw misplacement rates and provides critical support for minimally invasive surgical procedures, there have been no reports relating to the monitoring of quality control of the accuracy of this robot-assisted pedicle screw fixation procedure.

Methods. Patients with lumbar spinal stenosis scheduled to undergo surgery were randomly and equally assigned through 1:1 allocation to a robot-assisted minimally invasive posterior lumbar interbody fusion (Rom-PLIF) group or a conventional open posterior PLIF using freehand technique group. The accuracy of pedicle screw placement was evaluated using postoperative computed tomography. The primary outcome was the CUSUM analysis for monitoring the quality control of the accuracy of pedicle screw insertion between the Rom-PLIF and conventional open posterior PLIF using freehand technique groups.

Results. Of the 80 pedicle screws inserted in each group, 4 screws in the Rom-PLIF group, and 7 in the conventional open PLIF group, breached the pedicle. Of these 11 offending screws, 4 cases were categorized as grade B in the Rom-PLIF group, whereas 6 were grade B and 1 case was grade C in the Com-PLIF group, using the Gertzbein and Robbins classification. Throughout the monitoring period, there was no CUSUM test-derived indication that the quality of performance of the pedicle screw fixation procedure was inadequate in either group.

Conclusion. First, this study demonstrates the adequacy of quality control of robot-assisted pedicle screw fixation even early in the application period based on the CUSUM analysis. Second, the CUSUM test can be a useful tool for monitoring the quality of procedures related with spine surgery.

Key words: robot-assisted pedicle screw fixation, cumulative summation, freehand technique, posterior lumbar interbody fusion.

Level of Evidence: 2

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Recently, robot-assisted pedicle screw fixation has been introduced.1,2 This new technology significantly reduced the screw misplacement rate and is particularly useful in patients with challenging anatomy such as hypoplastic pedicle.1,3-5 In addition, these platforms provide critical support for minimally invasive surgical (MIS) procedures while simultaneously improving their accuracy and lowering the incidence of instrumented-related complications.5 As with any new technology, even when applied by experienced surgeons, the adoption of robotic-assisted surgery may require learning curves.5 Employment of quality control measures on surgical performance can effectively identify progress or challenges in the process.6

The cumulative summation (CUSUM) test, designed for monitoring quality control and/or learning curves, has already been implemented in numerous surgical settings, including the assessment of transplantation, laparoscopic and total hip replacement surgery outcomes.7-13 This statistical analysis can be applied to monitor any process with a binary outcome, allowing researchers to judge whether the initial or continued performance of a task is acceptable.13 Consequently, it has been shown to be of particular value in ensuring that performance is maintained during the introduction of a new procedure.
implant, or when using a technique with which a surgeon has little experience. 

Furthermore, it has also been used as an effective tool in the quality control of new technologies as they are initiated. 

This study applied the CUSUM test to prospectively monitor the quality control of robot-assisted pedicle screw fixation, operated by an experienced surgeon new to the use of robotics, and to compare it with that measured for freehand pedicle screw fixation. The working hypothesis of the study was that the robotic system improves accuracy and reliability of pedicle screw fixation at the initial stage of its application, even in minimally invasive procedures.

MATERIALS AND METHODS

Study Design and Participants

This analysis was performed within the framework of a prospective, randomized trial designed to evaluate the efficacy and safety of a robot-assisted pedicle screw fixation system. The intervention arm included 20 patients who underwent robot-assisted minimally invasive posterior lumbar interbody fusion (Rom-PLIF) surgery, whereas the control arm included 20 patients who underwent a conventional open PLIF (Cop-PLIF) procedure (Figure 1). All procedures were performed by the first author. The original study was approved by the hospital’s institutional review board, and all participants provided written informed consent before enrollment.

Our inclusion criteria were age 40 to 85 years, diagnosis of lumbar spinal stenosis including degenerative listhesis, lytic listhesis, foraminal stenosis, and central stenosis and patients who were scheduled to undergo spinal surgery. A diagnosis of lumbar spinal stenosis required presentation of one or more of the following symptoms: pain, numbness, or motor deficits in the lower extremities and buttocks, with confirmation of a stenotic lesion in the lumbar spine on magnetic resonance imaging. Exclusion criteria included a history of peripheral vascular disease, any concurrent serious medical condition causing disability, general poor health status including sepsis or cancer, and the inability to complete the questionnaires on pain and disability. All participants were admitted to the spinal center of a tertiary care teaching institution between December 2013 and April 2014. Patients were randomly assigned through 1 to 1 allocation to the Rom-PLIF or Cop-PLIF groups using a computer-generated randomization list, which was concealed from the first author before the randomized allocation. This study is registered at ClinicalTrials.gov, number NCT02121249.

Intervention Arm (Rom-PLIF)

Prior to this study, the first author participated in a manufacturer-sponsored training course and a training set of 5 clinical cases. Posterior decompression and fusion was performed by using the MIS technique. After cage insertion, robot-assisted (Renaissance; Mazor Robotics, Caesarea, Israel) pedicle screw fixation was performed using an MIS technique through a paramedian approach.

The robot device (a miniature, semiactive, parallel, and 6-df manipulator) and the workstation (Figure 2) comprised the robot system. As described in previous studies, use of the

Figure 1. Enrollment, randomization, assigned interventions, and follow-up of the study participants. Rom-PLIF indicates robot-assisted minimally invasive posterior lumbar interbody fusion; Cop-PLIF, conventional open posterior lumbar interbody fusion; CT, computed tomography.
robotic system requires preoperative planning before intraoperative execution. The preoperative planning was based on a computed tomographic (CT) scan of the spinal region of interest uploaded to the proprietary software (on the surgeon’s computer or on the workstation) and used in determining optimal screw length, diameter, positioning, and trajectories (Figure 2B). One of 2 attachment systems and matched platforms was used in each procedure—either the bed mount platform (which is fixed by a K-wire to a cranial spinous process and caudally attached to the operating table), or the clamp mount platform (a clamp attached to a spinous process with 2 stabilization K-wires inserted into caudal and cranial spinous processes). A fiducial array was placed on the mounting platform, and 2 intraoperative fluoroscopy images were taken (anteroposterior plane and 60° oblique to the lateral plane). The computer automatically merged the fluoroscopy images with the preoperative CT and registered the preoperative surgical blueprint with the physical location of the mounting platform. The robotic device was then mounted onto the platform, after which the system aligned itself with the planned trajectories. For each planned trajectory, the software determined which of 3 metal arms to attach to the robot (providing different working volumes) and cannulated tools were operated through this arm. Before drilling, the Peteron procedure was performed. A manual percussive tool was passed through the robotic arm to flatten the surfaces at the docking area of the cannulated tools (Figure 2A). This process prevents the cannulas from skidding off the desired trajectory (Figure 3). A drill guide was then inserted through the robot’s arm along the preoperatively planned trajectory, to the screw entrance point and the pedicles were opened with a 3-mm drill bit (Figure 2C). Guide wires were inserted in the pedicles, and after opening of all pedicles and inserting all guide wires, pedicle screws (SEXTANT; Medtronic Inc., Minneapolis, MN) were inserted over the guide wires by hand. Finally, rods were positioned between 2 screws.

Control Arm (Cop-PLIF)
A freehand (i.e., conventional), open, pedicle screw fixation was performed through a midline skin incision. The corresponding facet joints and transverse processes were exposed, to serve as the anatomical landmarks. In both study arms, care was taken not to violate the facet joint capsule, and the diameter of pedicle screw was determined on the basis of the preoperative CT scans. In both arms, after screw insertion, intraoperative radiograph was used for checking the location of screw placement; no screws were adjusted on the basis of this monitoring.

Outcome Measures
The primary outcome was the CUSUM analysis for monitoring of quality control of pedicle screw insertion accuracy between the Rom-PLIF and Cop-PLIF groups at the initial stage of application. The accuracy of pedicle screw insertion was evaluated by a blind and independent observer using postoperative axial, sagittal, and coronal views on CT scans,

Figure 2. Renaissance system components. A, Robot device with guide arm and Peteron instrument. B, Surgical planning in the workstation. C, Robot-guided pedicle drilling in the Rom-PLIF group. Rom-PLIF indicates robot-assisted minimally invasive posterior lumbar interbody fusion.

Figure 3. The Peteron instrument. A, Peteron instrument. B, Enlarged photograph of Peteron tip.
which were taken in all cases in both study arms. The pedicle screw positions were classified using a previously described 5-grade system: grade A, the screw is completely within the pedicle; grade B, the screw breaches the pedicle’s cortex by less than 2 mm; grade C, pedicle cortical breach less than 4 mm; grade D, pedicle cortical breach less than 6 mm; and grade E, pedicle cortical breach of 6 mm or more. In the CUSUM analysis, success of pedicle screw insertion was defined as a grade A state only, the other grades were considered violation of the pedicle, and were classified as an inaccurate screw insertion. The operating times, pedicle screw-related complications, and screw insertion angle were also analyzed in both arms.

CUSUM Analysis

The CUSUM analysis quantitatively scores the cumulative accuracy of pedicle screw placements. CUSUM scores of consecutive procedures performed by an individual operator are displayed as a line graph, with the x-axis representing the consecutive series of procedures and the y-axis representing the CUSUM score. The CUSUM score is determined using the formula:

\[ \text{CUSUM } C_n = \max(0, C_{n-1} + X_n - k) \]

where \( C \) = case; \( n \) = number of pedicle screw placements (in chronological, consecutive order); and \( X \) = outcome measure for the \( n \)th procedure. For binary outcome, \( X_n = 0 \) for a grade A screw placement, or success, and \( X_n = 1 \) for a pedicular violation, or failure. \( k \) is a prespecified standard of performance defined in terms of acceptable and unacceptable failure rates, which was calculated on the basis of \( \pi_1 \) and \( \pi_2 \) using methods described by Hawkins and Olwell (Table 1).

At the start, CUSUM \( C_0 = 0 \). At the \( n \)th procedure, \( X_n \) is the outcome measure \((0 \text{ or } 1)\) for the \( n \)th procedure. Performance with an acceptable standard has a negative score \((0 - k)\), and the chart is either flat or slopes downward, because the equation shows “the previous value \((C_n - 1)\) + negative score \((0 - k)\)” Performance with an unacceptable standard has a positive score \((1 - k)\), and the CUSUM chart slopes upward, because the equation shows “the previous value \((C_n - 1)\) + positive score \((1 - k)\).” Furthermore, because the equation has a maximum value between 0 and the score of sum, the graph will not slope downward below zero. When consecutive procedures performed by the same operator are of an unacceptable standard, the graph will continue to slope upward until it crosses a line drawn across the graph called the decision interval (limit \( b \)). When this occurs, the CUSUM chart is said to signal unsatisfactory performance, providing an early warning for implementation of corrective actions to prevent subsequent patients being harmed by adverse outcome resulting from deteriorating or substandard performance. The decision interval (limit \( b \)) is determined by specifying the in-control average run length and out-of-control average run length. In-control average run length is the average number of consecutive performance required for a CUSUM chart to cross a decision interval or signal during the period when the operator is performing at an acceptable level. This is akin to type I error in hypothesis testing. On the contrary, out-of-control average run length is the average number of procedures performed before the CUSUM chart signals, during the period when an individual is performing at an unacceptable level. It is a measure of sensitivity and is akin to power (1, type II error) or false-negative error in hypothesis testing.

In this study, the prespecified standard of performance was derived from previous literature. Previous studies have reported that about 90% and 95% accuracy has been reported using freehand technique and navigation system, respectively, if accurate placement of screw is defined as the penetration less than 2 mm or 3 mm. In this study, we defined the accurate placement was defined as intrapedicular placement. Therefore, the acceptable failure rate was less than 9%, and the unacceptable rate was more than 15% of procedure (pedicle screw placement) performed. Table 1 summarizes the specifications and parameter values used in CUSUM charting protocol for monitoring pedicle screw fixation.

RESULTS

Between December 2013 and April 2014, 43 patients were assessed for eligibility for the study; 40 patients met the inclusion criteria and were randomly assigned in a 1 to 1 ratio to one of the 2 study groups. Figure 1 shows the number of participants involved in the trial, from the eligibility assessment through the operation. Postoperative CT scans, obtained from all participants, were evaluated for pedicle screw placement accuracy.

The baseline characteristics of the participants were similar between the 2 groups (Table 2). All participants underwent a 1-segment PLIF for surgical treatment of lumbar spinal stenosis caused by degenerative spondylolisthesis, spondylolytic spondylolisthesis, or central foraminal stenosis. The mean age ± standard deviation was 64.4 ± 11.9 and 64.7 ± 8.6 years in the Rom-PLIF and Cop-PLIF groups, respectively \((P = 0.830)\). There were no significant differences in the diagnosis, operative

<table>
<thead>
<tr>
<th>TABLE 1. Cumulative Sum Charting Design for Monitoring the Performance of Pedicle Screw Fixation</th>
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<tr>
<td>Specification</td>
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<tr>
<td>Outcome measure for purpose of performance monitoring</td>
</tr>
<tr>
<td>Acceptable failure rate of performance for the outcome measure, ( \pi_1 )</td>
</tr>
<tr>
<td>Unacceptable failure rate of performance for the outcome measure, ( \pi_2 )</td>
</tr>
<tr>
<td>Reference value ( k )</td>
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<tr>
<td>Decision interval, limit ( b )</td>
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<tr>
<td>IC-ARL</td>
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<tr>
<td>OC-ARL</td>
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IC-ARL indicates in-control average run length; OC-ARL, out-of-control average run length.
TABLE 2. Descriptive Statistics of the Subjects in the Study

<table>
<thead>
<tr>
<th></th>
<th>Rom-PLIF (n = 20)</th>
<th>Cop-PLIF (n = 20)</th>
<th>P</th>
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</thead>
<tbody>
<tr>
<td>Age, mean ± SD, (yr)</td>
<td>64.4 ± 11.9</td>
<td>64.7 ± 8.6</td>
<td>0.830</td>
</tr>
<tr>
<td>Females, n (%)</td>
<td>9 (45)</td>
<td>12 (60)</td>
<td>0.342</td>
</tr>
<tr>
<td>BMI, mean ± SD, (kg/cm²)</td>
<td>25.3 ± 2.9</td>
<td>28.7 ± 10.2</td>
<td>0.187</td>
</tr>
<tr>
<td>BMD, mean ± SD, (g/cm²)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total lumbar</td>
<td>−0.57 ± 1.17</td>
<td>0.18 ± 1.74</td>
<td>0.118</td>
</tr>
<tr>
<td>Femur neck</td>
<td>−1.0 ± 0.87</td>
<td>−0.9 ± 1.06</td>
<td>0.674</td>
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<tr>
<td>Total hip</td>
<td>−0.32 ± 0.99</td>
<td>−0.17 ± 1.10</td>
<td>0.661</td>
</tr>
<tr>
<td>Diagnosis (n)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Degenerative listhesis</td>
<td>6</td>
<td>8</td>
<td>0.939</td>
</tr>
<tr>
<td>Lytic listhesis</td>
<td>7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Foraminal stenosis</td>
<td>10</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Central stenosis</td>
<td>10</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Screw diameter (n)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5 mm</td>
<td>50</td>
<td>70</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>5.5 mm</td>
<td>30</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Convergence angle, mean ± SD, (°)</td>
<td>20.25 ± 6.23</td>
<td>18.60 ± 5.83</td>
<td>0.106</td>
</tr>
<tr>
<td>Operating times, mean ± SD, (min)</td>
<td>217.75 ± 33.90</td>
<td>195 ± 46.90</td>
<td>0.103</td>
</tr>
<tr>
<td>Level (n)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2–L3</td>
<td>2</td>
<td>2</td>
<td>0.912</td>
</tr>
<tr>
<td>L3–L4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>L4–L5</td>
<td>9</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>L5–S1</td>
<td>7</td>
<td>5</td>
<td></td>
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Values are mean ± SD.

Rom-PLIF indicates robot-assisted minimally invasive posterior lumbar interbody fusion; Cop-PLIF, conventional open posterior lumbar interbody fusion; SD, standard deviation; BMD, bone mineral density.

TABLE 3. The Grade of Pedicle Screw Placement in Both Groups

<table>
<thead>
<tr>
<th>Grade of Pedicle Screw Placement</th>
<th>Rom-PLIF</th>
<th>Cop-PLIF</th>
</tr>
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<tbody>
<tr>
<td>A (n)</td>
<td>76</td>
<td>73</td>
</tr>
<tr>
<td>B (n)</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>C (n)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>D (n)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Rom-PLIF indicates robot-assisted minimally invasive posterior lumbar interbody fusion; Cop-PLIF, conventional open posterior lumbar interbody fusion.

Our study showed that the robot-assisted pedicle screw fixation system did not require time to reach an adequate level of performance, similar to the freehand technique. Throughout the monitoring period, there were no CUSUM-derived indications of inadequacy in the quality of performance of the pedicle screw fixation in either group (Figure 4). Failures were seen as a jump on the graph; however, the decision interval or limit b was never crossed in either group. Therefore, the performance of pedicle screw fixation using the robot-assisted system was considered adequate during the early application period and showed similar quality control as that of the freehand technique.

DISCUSSION

This analysis demonstrates the maintenance of quality control of robot-assisted pedicle screw fixation even in the early application period. Furthermore, the quality of performance of robot-assisted pedicle screw fixation is similar to using a freehand technique by an expert surgeon.

As the primary end point, the CUSUM chart showed adequate quality control for the accuracy of robot-assisted pedicle screw fixation in its early application. This suggests that adequate performance of robot-assisted pedicle screw fixation can be immediately reached, although almost all new procedures involve a learning curve before reaching a steady state. For the purpose of improving the accuracy of pedicle screw fixation, several methods have been introduced.24–26 Historically, a C-arm has been used during pedicle screw fixation. Recently, CT navigation has been introduced to visualize the precise anatomy of the pedicle, while reducing the cumulative radiation exposure.26 Intraoperative 2-dimensional and 3-dimensional fluoroscopy based navigation systems have also contributed to improved performance accuracy and reliability.26,27 However, new concerns about these high-technology systems have arisen because of a steep learning curve.27

robot-assisted to manual placement in the Rom-PLIF group. In the Cop-PLIF group, 70 and 10 screws were 6.5 and 5.5 mm in diameter, respectively, whereas 50 and 30 screws were 6.5 and 5.5 mm in diameter, respectively in the Rom-PLIF groups. In the Cop-PLIF group, 1 screw placement was revised because the patient had radicular pain caused by a misplaced screw of grade C. In the Rom-PLIF group, the bed mount and clamp mount were used in 17 and 3 patients, respectively.

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Our study showed that the robot-assisted pedicle screw fixation system did not require time to reach an adequate level of quality control. Therefore, the performance of pedicle screw fixation using the robot-assisted system was considered adequate during the early application period and showed similar quality control as that of the freehand technique.
Methods relying on CT navigation and fluoroscopy-based navigation provide intraoperative image guidance, whereas the robot-assisted pedicle screw fixation system mechanically guides the surgeon to the exact preoperatively planned trajectory. Therefore, if the surgeon is educated about brief surgical technique with the robot, the robot system will provide consistent results even in the early application period. These findings are in line with a recent study on the same robot system, which reported similar screw placement accuracy during the learning curve period.4

Previous reports on the accuracy of robot-assisted pedicle screw fixation have shown conflicting results.2–4,18 Although only 1 randomized controlled study demonstrated that pedicle screw fixation accuracy executed using the conventional freehand technique was superior to that of the robot-assisted technique,18 other studies have reported the outstanding accuracy of the robot-assisted pedicle screw fixation system including preliminary reports from a randomized controlled study.2–4,18 This study demonstrated high pedicle screw placement accuracy when using robotic assistance, with 76 screws categorized as grade A and 4 screws as grade B. A study by Ringel et al18 reported unfavorable results of the robot-assisted technique explained that one of the causes for the lower accuracy of the robotic-assisted pedicle screw placements in their study was due to the use of the bed mount platform. In our study, 85% of the screws were placed with the same platform, and was therefore not viewed as a factor leading to the difference in accuracy between this study and the study by Ringel.

Lateral skidding of the cannula was a central cause of inaccuracy in the study by Ringel et al.18 For preventing this, first, this study integrated the Peteron technique, which involves smoothing and flattening of the screw entry point before drilling, to prevent such skidding. Second, to prevent lateral skidding, the first author considered the lateral to medial screw trajectory (largest convergence angle if available in the robot system) as the ideal screw trajectory. The mean convergence angle was 20.25° ± 6.23° in the Rom-PLIF group. Because the lateral slope of the degenerative facet joint is steep, a larger convergence angle yields a larger angle between the lateral slope and screw insertion line, which may reduce the risk of lateral skidding, consequently improving overall accuracy. An earlier report discussed the significance of efficient preoperative planning of screw alignment in successful pedicle screw placement when using a robot.4 Third, the recently upgraded software, which allows for visualization of the iliac crests (which was mentioned by Ringel et al18 as another cause for inaccuracy) may have contributed to the improved accuracy of pedicle screw placement. The 3 improvements mentioned in the previous text in the system design and implementation are likely reasons why no screw was converted to manual placement in the Rom-PLIF group and why such a high accuracy was achieved in this group.

As expected, use of a process control chart and the CUSUM test successfully evaluated the quality control of this new technology with real-time information. In our study, the plot did not cross the limit h and no alarm was activated in either group, indicating that the robot-assisted fixation techniques maintained an adequate quality of performance similar to that achieved in a freehand technique, despite being a new methodology to the surgeon and the employment of a MIS approach. The CUSUM test presents numerous advantages over conventional methods.20 First, the CUSUM graph is intuitively comprehensible. Second, the unique feature of CUSUM is its ability to provide an early indication of a trend of deteriorating performance, prompting preventive and corrective measures.4 Third, compared with other conventional methods, it is objective and dynamic. Therefore, this tracks performance over time and refers to predetermined outcome standards. The standard of performance can also be modified on the basis of updated values derived from benchmarking or recent literatures. Fourth, a retrospective review by Spiegelhalter et al20 showed that the use of this statistical process control can detect inadequate performance much earlier than other statistical methods. Therefore, CUSUM can be applied not only to monitor the quality control of a certain procedure, but also to accurately track the learning curve in surgical procedures.20,29,32

Several limitations in this study should be acknowledged. First, the ratios of screw diameters used in both groups were significantly different, which may have influenced the interpretation of screw placement accuracy. However, failure of pedicle screw placement was defined very conservatively in this study; grade B breaching, was regarded as a failure...
although it has been considered a successful placement in most previous studies.24,26 Second, operating times were not considered in the measurement of performance quality. In fact, there was no significant difference in operating times between Rom-PLIF and Cop-PLIF groups (217.75 ± 33.90 and 195 ± 46.90, respectively, P = 0.103). Although previous studies on learning curves have regarded this as a surrogate of performance quality,12,28,29 it is rarely related to clinical outcomes. Third, although costs and benefits of technology-driven instrumented lumbar fusion have been emerged as the critical issue for assessing the new technology, this study did not deal with such an issue. Considering the present results and a previous study, however, MIS with the robot-assisted pedicle screw fixation might have benefits about the lower complication rate and a lower number of residual events due to the accurate pedicle screw placement, whereas this has inherent cost of new robot technology.31

**CONCLUSION**

Our study demonstrates adequate quality control of robot-assisted pedicle screw fixation even in the early application period. Furthermore, CUSUM can be a useful tool for monitoring the quality of procedures related to spine surgery.

**Key Points**

- This study demonstrates the adequate quality control of robot-assisted pedicle screw fixation even early in the application period.
- The accuracy of robot-assisted pedicle screw fixation in minimally invasive spinal fusions is similar to pedicle screw fixation using freehand technique in an open surgical approach by an expert surgeon.
- CUSUM can be a useful tool for monitoring of the quality of procedures associated with spine surgery.

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