ISSN 1220-8841 (Print)
ISSN 2344-4959 (Online)

ROMANIAN
NEUROSURGERY

Vol. XXXVII | No. 3 September 2023

Percutaneous pedicle screw fixation. A comprehensive review of techniques, outcomes, and advancements

Muhammad Jehanzeb,
Ahtesham Khizar,
Naeem Ul Hassan,
Khawar Anwar,
Moin Islam Arain,
Asif Bashir

DOI: 10.33962/roneuro-2023-058

Romanian Neurosurgery (2023) XXXVII (3): pp. 317-327
DOI: 10.33962/roneuro-2023-058
www.journals.lapub.co.uk/index.php/roneurosurgery

Percutaneous pedicle screw fixation. A comprehensive review of techniques, outcomes, and advancements

Muhammad Jehanzeb, Ahtesham Khizar, Naeem Ul Hassan, Khawar Anwar, Moin Islam Arain, Asif Bashir

Punjab Institute of Neurosciences, Lahore, PAKISTAN

ABSTRACT

Percutaneous pedicle screw fixation (PSF) has emerged as a promising alternative to traditional open surgical approaches for spinal stabilization. Pedicle screws are inserted through percutaneous access sites without substantial soft tissue dissection. To ensure proper screw insertion, the procedure employs fluoroscopic or image-guided navigation devices. The popularity of percutaneous PSF has accelerated because of its prospective advantages and the mounting body of research demonstrating its effectiveness and safety. However, there are a few drawbacks to the procedure, such as a longer learning curve for surgeons, poor visibility when inserting screws, and a requirement for specialized tools and imaging guiding systems. This article provides a comprehensive review of the technique of percutaneous PSF, its clinical outcomes, and recent advancements in the field. It also aims to analyze the efficacy, safety, and limitations of percutaneous PSF, as well as explore the evolving technologies and techniques that have contributed to its improved application.

Keywords
spine,
lumbar vertebrae,
thoracic vertebrae,
pedicle screws,
fracture fixation

Corresponding author:
Muhammad Jehanzeb

Department of Neurosurgery.
Punjab Institute of Neurosciences,
Lahore, Pakistan

drjehanzeb28@gmail.com

ISSN online 2344-4959
© Romanian Society of Neurosurgery

First published
September 2023 by
London Academic Publishing
www.lapub.co.uk

INTRODUCTION

Spinal instability and deformities, such as degenerative disc disease, spondylolisthesis, and spinal fractures, often require surgical intervention for stabilization and restoration of spinal alignment. Traditional open surgical approaches for pedicle screw fixation (PSF) have been widely used and proven effective. However, these approaches are associated with significant tissue disruption, prolonged hospital stays, higher complication rates, and prolonged recovery periods.[1,2] Percutaneous PSF, also known as minimally invasive PSF, has emerged as an alternative technique to address these drawbacks. It involves the insertion of pedicle screws through percutaneous access points without extensive soft tissue dissection. The technique utilizes fluoroscopic or image-guided navigation systems to facilitate accurate screw placement.[3,4]

The significance of percutaneous PSF lies in its potential to provide several advantages over open surgical techniques. Firstly, the percutaneous approach minimizes tissue damage, leading to reduced blood loss, postoperative pain, and soft tissue complications. This approach allows for preservation of the paraspinal muscles, which can help maintain spinal stability and enhance postoperative functional outcomes. Secondly, the reduced tissue disruption may result in shorter hospital stays, faster recovery, and improved patient satisfaction. Furthermore, percutaneous PSF offers the potential for reduced intraoperative radiation exposure for both patients and surgical staff.[3]

Understanding the background and significance of percutaneous PSF is crucial for healthcare professionals and researchers involved in spinal surgery. It enables them to make informed decisions regarding surgical approaches, consider alternative techniques, and contribute to the ongoing advancements and developments in spinal stabilization procedures.[5,6] The adoption of percutaneous PSF has gained momentum due to its potential benefits and growing evidence supporting its safety and efficacy. However, the technique also presents challenges, including a steeper learning curve for surgeons, limited visualization during screw placement, and the need for specialized instruments and imaging guidance systems. Therefore, further research and exploration are needed to optimize the technique, refine patient selection criteria, and evaluate long-term outcomes. By discussing the current challenges and limitations associated with percutaneous PSF, this article aims to identify potential areas for future research and development. Exploring emerging technologies, refining techniques, and addressing limitations can contribute to further improving patient outcomes and advancing the field.

Discussion

Biomechanical principles underlying percutaneous pedicle screw fixation

Percutaneous PSF is a technique used to achieve spinal stability and fusion by placing screws through percutaneous access points into the pedicles of vertebral bones. The biomechanical principles underlying this technique are essential to understand its efficacy and to optimize surgical outcomes. The key biomechanical principles associated with percutaneous PSF are given below:

a. **Screw purchase and stability:** The primary biomechanical objective of PSF is to achieve secure screw purchase within the pedicle and maximize stability. Screw purchase refers to the engagement of the screw threads within the pedicle bone, allowing for effective load transfer and resistance to pull-out forces.[7]

b. **Load sharing and stability:** Percutaneous PSF provides load sharing and stability to the spinal column. The screws are inserted into the pedicles of adjacent vertebrae, allowing for the transfer of axial and torsional loads. By engaging the pedicles, the screws enhance the stability of the construct, reducing motion at the treated segment and promoting fusion.[7,8]

c. **Correction of spinal deformities:** PSF is frequently employed to correct spinal deformities such as scoliosis, kyphosis, and spondylolisthesis. The technique allows for three-dimensional deformity correction by applying corrective forces to the vertebrae through the screws and connecting rods.[9]

d. **Three-column concept:** Percutaneous PSF follows the three-column concept, which aims to restore and maintain the stability of the anterior, middle, and posterior columns of the spine. The screws inserted into the pedicles provide posterior column stability, complementing the anterior column support provided by interbody fusion or other anterior procedures.[10,11]

e. **Screw-bone interface:** The success of percutaneous PSF relies on the biomechanical stability of the screw-bone interface. Achieving adequate purchase within the pedicle is essential to prevent screw loosening, pull-out, or breakage. Factors influencing the screw-bone interface include screw size, design, thread profile, cortical bone integrity, and bone quality.[12]

f. **Stress distribution and preservation of spinal motion segments:** PSF should distribute stresses evenly across the instrumented spinal segments, minimizing stress concentrations and avoiding adjacent segment degeneration. The technique aims to preserve the range of motion of the instrumented spinal segments.[7]

g. **Biomechanical considerations for osteoporotic spines:** Osteoporosis is characterized by a decrease in bone density and quality, which can compromise the screw-bone interface and stability of PSF. Osteoporotic vertebrae have lower bone mineral density, diminished trabecular bone structure, and increased susceptibility to screw loosening, pullout, or vertebral body fracture. Therefore, careful screw trajectory planning and selection of appropriate screw size and design are crucial in osteoporotic spines.[7]

Percutaneous Pedicle Screw Fixation Techniques

Percutaneous PSF techniques have evolved to improve surgical outcomes and minimize tissue trauma compared to traditional open approaches. The use of image guidance and navigation systems further enhances the accuracy and safety of percutaneous pedicle screw placement. A description of percutaneous techniques and the role of image guidance and navigation systems is given below:

A. **Percutaneous techniques:** Percutaneous PSF involves the insertion of screws through small incisions, typically aided by fluoroscopy or navigation systems, without extensive soft tissue dissection. Key steps include:

   a. **Patient positioning:** The patient is positioned in a prone position on the operating table, allowing access to the targeted vertebrae.
   b. **Percutaneous access points:** Small incisions are made near the targeted vertebrae to access the pedicles. Dilators or cannulas are then used to create a pathway to the pedicle entry point.
   c. **Pedicle screw insertion:** Pedicle screws of appropriate length and diameter are inserted into the pedicles under fluoroscopic guidance or navigation assistance. The screws are carefully advanced, ensuring proper engagement within the pedicle.
   d. **Rod placement and fixation:** Once the screws are in place, connecting rods or plates are attached to achieve spinal alignment and stability. The rods are contoured to match the natural curvature of the spine.
   e. **Closure:** The incisions are closed, and appropriate postoperative care is provided to the patient.

B. **Image guidance and navigation systems:** Image guidance and navigation systems play a crucial role in percutaneous PSF, providing real-time visualization and assisting in accurate screw placement. These systems utilize preoperative imaging such as Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) scans and intraoperative imaging such as fluoroscopy or 3D navigation to guide the surgical procedure. Key components include:

   a. **Fluoroscopy:** Fluoroscopy provides live X-ray imaging during the surgery, enabling the surgeon to visualize the bony landmarks, pedicles, and screw trajectories. It helps ensure accurate screw placement and assess the quality of screw purchase.
   b. **3D Navigation systems:** 3D navigation systems use preoperative imaging data to create a virtual 3D representation of the patient's spine. Real-time tracking of instruments and screws is facilitated using optical or electromagnetic sensors. The system provides guidance and feedback to assist the surgeon in precise screw placement.
   c. **Robotic-assisted navigation:** Robotic-assisted navigation systems utilize robotic arms and intraoperative imaging to guide the surgeon's movements. The robotic system assists in preoperative planning, intraoperative screw trajectory guidance, and screw insertion.
   d. **Optical navigation:** Optical navigation systems use infrared cameras and specialized instruments with reflective markers to track their positions relative to the patient's anatomy. The system provides real-time feedback on the instrument's location and trajectory.[13,14]

Explanation of procedural steps and instrumentation

Percutaneous PSF is a minimally invasive technique used for spinal stabilization and fusion. The procedure involves specific steps and utilizes specialized instrumentation. Here is an explanation of the procedural steps and instrumentation commonly employed in percutaneous PSF:

a. **Preoperative planning:** CT or MRI scans are obtained to evaluate the spinal anatomy, assess the pedicle morphology, and determine the appropriate screw size and trajectory.
b. **Patient positioning:** The patient is positioned prone on the operating table, with padding and

supports to maintain proper alignment and accessibility to the targeted vertebrae.

c. **Percutaneous access/skin incisions:** Small incisions, typically ranging from 1 to 2 cm in length, are made near the targeted vertebrae to access the pedicles.
d. **Pedicle preparation and screw placement:** 1) Pedicle identification: Fluoroscopic guidance or navigation systems are used to identify the entry points of the pedicles. 2) Pedicle preparation: Sequential dilators or cannulas are inserted through the incisions to create a pathway to the pedicles while minimizing soft tissue disruption. 3) Screw insertion: Pedicle screws, with self-drilling and self-tapping features, are carefully inserted into the pedicles. Fluoroscopic guidance or navigation assistance is used to ensure accurate screw placement and trajectory.
e. **Rod placement and fixation:** 1) Rod bending: Connecting rods, typically made of titanium or stainless steel, are contoured to match the natural curvature of the spine and correct any deformities. 2) Rod insertion: The rods are inserted into the previously placed rod connectors or connectors on the pedicle screws. 3) Rod fixation: Rods are secured in place using set screws or locking mechanisms on the rod connectors, providing stability and maintaining proper alignment.
f. **Closure and postoperative care:** The incisions are closed using sutures or adhesive strips, and sterile dressings are applied. Postoperative care includes monitoring for complications, pain management, and rehabilitation protocols tailored to the patient's specific condition.[15,16]

Comparison of percutaneous techniques with open surgical approaches

Percutaneous PSF techniques have gained popularity as an alternative to open surgical approaches for spinal stabilization. Several studies have compared the outcomes and advantages of percutaneous techniques with traditional open surgical approaches. Here, we provide a comparison between percutaneous techniques and open surgical approaches, supported by relevant references.

a. **Surgical trauma and complications:** Percutaneous techniques involve smaller incisions, minimal soft tissue dissection, and reduced muscle damage compared to open approaches. This results in decreased blood loss, lower infection rates, and shorter hospital stays.As compared to Open Surgical Approaches. Open surgical approaches require larger incisions, extensive muscle dissection, and more tissue trauma. These factors can contribute to increased blood loss, higher infection rates, and longer hospital stays.[17]
b. **Surgical time and operative efficiency:** Percutaneous techniques generally require a shorter surgical time compared to open approaches. The reduced soft tissue dissection and simpler instrumentation can contribute to faster procedure as compared to Open Surgical Approaches. Open surgical approaches typically involve more extensive exposure, requiring longer surgical times. The complexity of soft tissue handling and the need for additional steps may contribute to increased operative time.[18]
c. **Postoperative pain and recovery:** Percutaneous techniques are associated with less postoperative pain due to reduced muscle damage and tissue trauma. Patients may experience a quicker recovery, earlier ambulation, and a faster return to daily activities as compared to Open Surgical Approaches. Open surgical approaches can result in more postoperative pain due to extensive soft tissue dissection. The recovery period may be longer, with delayed mobilization and slower return to daily activities.[19]
d. **Correction of spinal deformities:** Percutaneous techniques can achieve comparable deformity correction to open surgical approaches in select cases. However, complex deformities may require open surgery for better visualization and three-dimensional correction. Open surgical approaches allow direct visualization of the spinal deformity, facilitating extensive correction, osteotomies, and fusion. These approaches are often preferred for complex deformities requiring substantial correction.[20,21]

Advantages and limitations of percutaneous pedicle screw fixation

Percutaneous PSF has gained popularity as a minimally invasive technique for spinal stabilization. Here is a discussion of the advantages and limitations of percutaneous pedicle screw fixation:

A. Advantages:

a. **Minimally invasive approach:** Percutaneous PSF involves smaller incisions and reduced soft tissue disruption compared to open surgical approaches. This results in less postoperative pain, reduced blood loss, shorter hospital stays, and faster recovery for patients.[3,23]
b. **Preservation of muscle and soft tissue:** The percutaneous technique minimizes disruption to the surrounding muscles and soft tissues, leading to decreased muscle trauma and potentially faster rehabilitation. Preservation of the muscle and soft tissue structures can help maintain spinal stability and reduce the risk of muscle atrophy.[22]
c. **Reduced infection rates:** The smaller incisions and limited soft tissue dissection associated with percutaneous pedicle screw fixation have been linked to lower rates of surgical site infections compared to open techniques.[22]
d. **Improved cosmesis:** The smaller incisions in percutaneous PSF result in less visible scarring and improved cosmetic outcomes compared to open surgery.[3]
e. **Reduced surgical morbidity:** Percutaneous PSF has been associated with lower rates of complications such as blood loss, wound complications, and postoperative infections compared to open techniques, resulting in reduced surgical morbidity.[22,23]

B. Limitations:

a. **Technical challenges:** Percutaneous PSF requires advanced surgical skills and familiarity with fluoroscopic guidance or navigation systems. The procedure can be technically demanding and may have a learning curve for surgeons.[3]
b. **Limited visualization:** The limited visualization provided by percutaneous techniques may make it challenging to address complex spinal pathologies or ensure precise screw placement. In some cases, conversion to an open technique may be necessary for optimal visualization and screw placement.[22]
c. **Radiation exposure:** The use of fluoroscopic guidance or navigation systems in percutaneous PSF exposes the patient and surgical team to ionizing radiation. Proper radiation safety measures should be taken to minimize radiation exposure.[3]
d. **Fusion rates:** Although percutaneous PSF has shown comparable fusion rates to open techniques in several studies, the long-term durability and stability of fusion achieved with percutaneous methods are still subjects of ongoing research and debate.[6,22]
e. **Limited indications:** Percutaneous PSF may not be suitable for all spinal pathologies or complex deformities. Cases involving severe instability, significant vertebral destruction, or extensive multi-level involvement may require open surgical approaches for optimal outcomes.[3]

It is important to consider the advantages and limitations of percutaneous PSF on a case-by-case basis, taking into account the patient's specific condition and individual risk factors. Collaboration between the surgeon and the patient is essential in making informed decisions about the most appropriate surgical approach.

Advancements in Percutaneous Pedicle Screw Fixation

Percutaneous PSF has undergone advancements and refinements over time, leading to improved techniques and outcomes. Here are some notable advancements in percutaneous PSF:

a. **Navigation and image guidance:** The integration of navigation systems and image guidance technologies, such as fluoroscopy, CT scans, or intraoperative 3D imaging, has enhanced the accuracy and precision of percutaneous pedicle screw placement. These technologies allow real-time visualization of the surgical field, aiding in optimal screw trajectory and reducing the risk of misplacement.[3,22]
b. **Robotic assistance:** Robotic-assisted percutaneous PSF is an emerging advancement that offers increased precision and control during screw placement. Robotic systems provide intraoperative navigation, image guidance, and robotic arm assistance, enhancing the surgeon's ability to achieve accurate screw trajectories.

Robotic assistance can potentially improve the safety and efficacy of percutaneous PSF.[23]

c. **Cement augmentation:** Cement augmentation techniques, such as cement-augmented screws or vertebroplasty/kyphoplasty, have been applied in percutaneous PSF to enhance screw stability and fixation, especially in osteoporotic spines. The use of bone cement can improve screw purchase within the pedicle and increase construct rigidity. This advancement has shown promising results in improving screw pullout strength and reducing the risk of screw loosening or failure.[24,25]

d. **Expandable pedicle screws:** Expandable pedicle screws are designed to be inserted in a compact form and then expanded within the pedicle, providing improved anchorage and fixation. These screws allow for greater bone-screw interface contact, potentially enhancing biomechanical stability. Expandable pedicle screws have shown promise in improving screw pullout strength and reducing the risk of screw loosening or migration.[24,25]

e. **Biomechanical studies and finite element analysis:** Advancements in biomechanical studies and finite element analysis have contributed to a better understanding of the biomechanical properties and load-sharing characteristics of percutaneous pedicle screw fixation. These studies help optimize screw design, implant selection, and surgical techniques, leading to improved construct stability and patient outcomes.[26] Biomechanical studies involving in vitro testing, cadaveric studies, and animal models provide valuable insights into the load-sharing characteristics, stability, and strength of percutaneous PSF. These studies help assess the effects of various factors, such as screw design, screw length and diameter, bone quality, and loading conditions, on the biomechanical performance of the construct. They aid in optimizing screw placement techniques, evaluating the risk of screw pullout or failure, and determining the appropriate surgical parameters for achieving desired outcomes.[26,27] Finite element analysis (FEA) is a computational technique widely used in biomechanical studies of percutaneous pedicle screw fixation. FEA allows for the creation of a virtual model of the spinal segment, incorporating anatomical details, material properties, and boundary conditions. Through FEA, researchers can simulate and analyze the distribution of stresses and strains within the spinal construct, predict the response to different loading scenarios, and evaluate the impact of various variables on the biomechanical performance. This analysis provides insights into the stress distribution along the screws, vertebral bodies, and intervertebral discs, helping optimize the design, placement, and fixation techniques.[28,29] Overall, biomechanical studies and finite element analysis play a critical role in improving our understanding of percutaneous PSF, guiding surgical decision-making, and enhancing patient outcomes.

These advancements in percutaneous PSF aim to enhance surgical precision, optimize screw placement, improve construct stability, and expand the indications for minimally invasive spinal surgeries. However, further research and long-term clinical studies are needed to validate these advancements and evaluate their impact on patient outcomes.

Overview of emerging technologies, such as Robotic Assistance and Augmented Reality

Emerging technologies are transforming the field of spinal surgery, offering new tools and techniques that improve surgical precision, patient outcomes, and surgical workflow. Two notable emerging technologies in spinal surgery are robotic assistance and augmented reality. Here is an overview of these technologies:

A. **Robotic Assistance:** Robotic-assisted spinal surgery involves the use of robotic systems to enhance surgical precision, accuracy, and safety. These systems provide surgeons with real-time navigation, image guidance, and robotic arm assistance, allowing for improved screw placement, optimal trajectory, and increased procedural efficiency. Advantages of robotic assistance are:

   a. **Improved accuracy:** Robotic systems enable highly accurate preoperative planning and intraoperative execution, resulting in precise screw placement and reduced risk of complications.

b. **Enhanced safety:** Real-time intraoperative navigation and feedback help prevent potential errors, such as screw misplacement or neural damage.
c. **Workflow efficiency:** Robotic assistance can streamline surgical workflow, decrease surgical time, and potentially reduce radiation exposure for both the patient and surgical team.[30,31]

B. **Augmented Reality:** Augmented reality (AR) is a technology that overlays virtual information onto the real-world surgical view, providing surgeons with real-time guidance and anatomical visualization during surgery. AR systems utilize advanced imaging techniques, such as preoperative CT/MRI scans, to project 3D virtual models onto the surgical field, assisting in accurate anatomical localization and surgical navigation. Advantages of augmented reality are:

a. **Enhanced visualization:** AR technology allows surgeons to visualize and interact with anatomical structures, implants, and surgical plans in real-time, improving accuracy and decision-making.
b. **Precise instrument guidance:** AR systems provide real-time visual guidance for instrument navigation, aiding in precise screw placement, tumor resection, or spinal deformity correction.
c. **Surgical education and training:** AR can facilitate surgical education and training by providing a virtual environment for surgical simulation and rehearsal.[32,33]

Both robotic assistance and augmented reality hold great potential in advancing spinal surgery by improving surgical accuracy, safety, and outcomes. However, it is important to note that these technologies are still evolving, and further research, clinical validation, and widespread adoption are needed to fully assess their impact on patient outcomes and to determine their optimal applications in the field of spinal surgery.

Clinical outcomes and complications

Literature review evaluating the efficacy and safety of percutaneous PSF demonstrates that percutaneous PSF has gained popularity as a minimally invasive technique for spinal stabilization. Numerous clinical studies have been conducted to evaluate the efficacy and safety of this procedure. Here is a review of selected clinical studies that have examined the outcomes of percutaneous PSF:

Tian NF et al.[5] in their meta-analysis compared the accuracy of pedicle screw insertion using different assisted methods, including percutaneous techniques. The study found that percutaneous pedicle screw insertion had comparable accuracy to open techniques and other assisted methods, with lower radiation exposure and reduced blood loss.

Titan F et al.[34] in their meta-analysis compared percutaneous PSF with open techniques for thoracolumbar fractures. The study found that percutaneous fixation resulted in similar clinical outcomes, including pain relief, functional improvement, and complication rates, with shorter surgical time, reduced blood loss, and shorter hospital stays compared to open techniques.

Phan K et al.[15] in their systematic review and meta-analysis compared percutaneous PSF with open techniques for thoracolumbar fractures. The study found that percutaneous fixation had similar clinical outcomes, including pain relief, functional improvement, and complication rates, with reduced blood loss, shorter hospital stays, and lower infection rates compared to open techniques.

These studies suggest that percutaneous PSF is associated with favorable patient outcomes, including comparable fusion rates and functional improvements compared to open techniques, along with benefits such as reduced complications, less blood loss, less radiation exposure, shorter surgical time and shorter hospital stays.

Evaluation of the impact of advancements on surgical outcomes

The advancements in percutaneous PSF techniques and technologies have the potential to significantly impact surgical outcomes in terms of accuracy, safety, patient recovery, and long-term success. Several studies have evaluated the impact of these advancements on surgical outcomes, and here we present a summary of their findings:

a. **Accuracy and screw placement:** The integration of navigation systems and robotic assistance has been shown to improve the accuracy of screw placement in percutaneous PSF. Tian NF et al.[14] conducted a meta-analysis comparing minimally invasive techniques with open surgery and found that navigation-guided percutaneous PSF had a higher accuracy rate and lower screw misplacement rate compared to conventional techniques.

b. **Surgical efficiency and time:** Robotic-assisted percutaneous pedicle screw fixation has shown potential in improving surgical efficiency and reducing operative time. Huang J et al.[23] reported in their review that robotic-assisted procedures were associated with shorter surgical times compared to conventional techniques. The advanced imaging and robotic arm assistance provided by robotic systems contribute to a more streamlined workflow, leading to potential time savings.
c. **Patient-specific planning and outcomes:** The use of patient-specific planning and customized screw trajectories in percutaneous pedicle screw fixation has shown promising outcomes. Preoperative planning of pedicle screw placement done using a 3D printed spine model has been shown to increase the accuracy of pedicle screw placement, with a 91% acceptance rate, according to a study by Xu W et al.[35] on patients with middle-upper thoracic spine trauma.
d. **Cement augmentation and stability:** The use of cement augmentation techniques, such as cement-augmented screws or vertebroplasty/kyphoplasty, has been shown to enhance screw stability and reduce complications, particularly in osteoporotic patients. Liu D et al.[28] conducted a systematic review and meta-analysis and reported that cement augmentation significantly improved screw pullout strength and reduced the risk of screw loosening or failure.

These studies highlight the positive impact of advancements in percutaneous pedicle screw fixation techniques on surgical outcomes, including improved accuracy, surgical efficiency, patient-specific planning, and enhanced screw stability.

Future directions and challenges

Percutaneous PSF has shown promising results in various studies and has gained popularity in clinical practice. However, ongoing research aims to further enhance the technique and explore potential areas for improvement. Here, we discuss some of the current research trends and areas for advancement:

a. **Navigation and Robotics:** Ongoing research focuses on the integration of navigation systems and robotic assistance to improve the accuracy and safety of percutaneous pedicle screw placement. These technologies offer real-time intraoperative guidance, improved screw trajectory planning, and reduced radiation exposure. Studies are investigating the effectiveness and cost-effectiveness of these advanced techniques in achieving optimal outcomes.[23]
b. **Augmented Reality (AR) and Virtual Reality (VR) :** The integration of AR and VR technologies holds great promise for enhancing surgical planning, visualization, and intraoperative guidance in percutaneous pedicle screw fixation. AR/VR can provide surgeons with real-time feedback, improved depth perception, and enhanced anatomical visualization. These technologies have the potential to improve accuracy, reduce surgical time, and facilitate the adoption of percutaneous techniques in more complex cases.[32,33]
c. **Biomechanical studies and Material innovation:** Further biomechanical studies and material innovation can contribute to the refinement of percutaneous PSF. Evaluating the biomechanical stability of percutaneous constructs under different loading conditions and studying the long-term effects on fusion rates and implant failure can provide valuable insights. Additionally, advancements in implant materials and coatings can enhance the osseointegration of percutaneous pedicle screws and improve their overall biomechanical performance.[26,28,29]
d. **Patient selection and Outcome measures:** Ongoing research emphasizes the importance of appropriate patient selection criteria and standardized outcome measures to evaluate the effectiveness of percutaneous PSF. Studies are investigating patient-specific factors, such as age, bone quality, and pathology, to determine the ideal candidates for percutaneous techniques. Additionally, research focuses on developing standardized outcome measures to assess clinical outcomes, fusion rates, functional outcomes, and complications consistently.[36]

e. **Cost-effectiveness analysis:** The economic impact of percutaneous PSF compared to open surgery is an important area of investigation. Studies are assessing the cost-effectiveness and cost-benefit of percutaneous techniques by considering factors such as operative time, length of hospital stay, reoperation rates, and overall healthcare costs. These analyses contribute to healthcare decision-making and resource allocation.[36]
f. **Learning curve and Technical expertise:** The percutaneous approach requires specialized training and technical expertise. Surgeons must become proficient in percutaneous techniques, including image guidance and navigation systems. The learning curve for percutaneous PSF can be steep, and initial cases may have longer operative times and higher complication rates. However, with experience, surgeons can overcome these challenges and achieve satisfactory outcomes.[37]
g. **Limited visualization and exposure:** Compared to open surgery, percutaneous techniques provide limited visualization and exposure of the surgical site. This can make it challenging to address complex anatomical variations, severe deformities, or multi-level pathologies. In such cases, open surgery may be more appropriate to achieve optimal correction and decompression.[28]
h. **Risk of screw misplacement:** The percutaneous technique relies heavily on fluoroscopic or intraoperative navigation guidance for screw placement. However, despite these aids, there is a risk of screw misplacement, especially in cases with complex anatomy or poor visualization. Screw malposition can lead to complications such as neurovascular injury, implant failure, or inadequate biomechanical stability.[5]
i. **Limited accessibility and versatility:** Percutaneous techniques may not be suitable for all patients and pathologies. Factors such as severe obesity, extensive scarring, or anatomical variations can limit the accessibility and feasibility of percutaneous pedicle screw fixation. Additionally, percutaneous techniques may have limitations in addressing complex spinal deformities or extensive multi-level pathologies, where open surgery may be more appropriate.
j. **Limited ability for direct decompression:** Percutaneous PSF focuses primarily on achieving spinal stability and fusion but may not directly address neural decompression. In cases where neural compression is a significant concern, additional minimally invasive or open decompression techniques may be necessary.
k. **Patient-specific planning and 3D printing:** Advancements in patient-specific planning and 3D printing technology can facilitate precise preoperative planning and improve screw trajectory accuracy in percutaneous PSF. The use of patient-specific anatomical models and guides, created through 3D printing, allows for personalized surgical approaches. This technology enables surgeons to anticipate anatomical variations, optimize screw placement, and improve overall surgical outcomes.[35]
l. **Advanced Navigation and Robotics:** Continued advancements in navigation systems and robotic assistance are expected to refine percutaneous pedicle screw fixation. Real-time feedback, improved accuracy, and enhanced precision offered by these technologies can further optimize screw placement and reduce the risk of complications. Additionally, the integration of artificial intelligence and machine learning algorithms may enable automated screw trajectory planning, improving surgical efficiency.[23]

Exploring these future directions in technique refinement and patient selection has the potential to enhance the efficacy, safety, and applicability of percutaneous PSF in clinical practice. These advancements aim to improve surgical outcomes, expand the patient population eligible for percutaneous techniques, and enhance the overall efficacy of the procedure.

Conclusions

Percutaneous PSF is shown to be an effective and safe technique for achieving spinal stability and fusion. Clinical studies have reported high fusion rates and satisfactory functional outcomes in various spinal pathologies, including degenerative conditions, trauma, and deformities. Comparative studies and meta-analyses have consistently shown that percutaneous techniques offer comparable or even superior outcomes compared to open surgical approaches. These studies have demonstrated shorter operative times, reduced blood loss, decreased postoperative pain, and faster recovery with percutaneous pedicle screws fixation. Patient outcomes following percutaneous PSF are generally positive. The majority of patients experience improved pain relief, restoration of spinal alignment, and functional recovery. However, careful patient selection is crucial to ensure optimal outcomes, and certain patient factors, such as obesity or extensive scarring, may limit the suitability of percutaneous techniques. While percutaneous PSF has demonstrated favorable outcomes, there are potential complications and limitations associated with the technique. These include screw misplacement, neurovascular injury, inadequate decompression, and limited versatility in addressing complex spinal deformities or multi-level pathologies. Advancements in image guidance, navigation systems, augmented reality, and robotic assistance are enhancing the accuracy and precision of percutaneous PSF. Patient-specific planning and 3D printing technologies are also facilitating personalized surgical approaches. Furthermore, ongoing research is exploring the impact of these advancements on surgical outcomes and expanding the eligibility of percutaneous techniques to more challenging cases. In short, percutaneous PSF is a valuable surgical technique for achieving spinal stabilization and fusion. It offers several advantages over open surgery, including reduced tissue trauma, faster recovery, and comparable outcomes. However, careful patient selection and surgeon expertise are crucial for optimizing outcomes and minimizing complications. Continued research and technological advancements hold promise for further refining the technique and expanding its applications in the future.

List of Abbreviations

PSF: Pedicle screw fixation;
CT: Computed Tomography;
MRI: Magnetic Resonance Imaging;
FEA: Finite Element Analysis;
AR: Augmented Reality;
VR: Virtual Reality.

References

1. Anand N, Baron EM, Khandehroo B, Kahwaty S. Long-term 2- to 5-year clinical and functional outcomes of minimally invasive surgery for adult scoliosis. Spine (Phila Pa 1976). 2013;38(18):1566-1575. doi:10.1097/BRS.0b013e31829cb67a
2. Hu X, Ohnmeiss DD, Lieberman IH. Robotic-assisted pedicle screw placement: lessons learned from the first 102 patients. Eur Spine J. 2013;22(3):661-666. doi:10.1007/s00586-012-2499-1
3. Phan K, Rao PJ, Kam AC, Mobbs RJ. Minimally invasive versus open transforaminal lumbar interbody fusion for treatment of degenerative lumbar disease: systematic review and meta-analysis. Eur Spine J. 2015;24(5):1017-1030. doi:10.1007/s00586-015-3903-4
4. Kehr, P. Daniel H. Kim, Alexander R. Vaccaro, Richard G. Fessler, Kris E. Radcliff (Eds): Spinal instrumentation: challenges and solutions. Eur J Orthop Surg Traumatol 29, 237 (2019). doi:10.1007/s00590-018-2256-1
5. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. Eur Spine J. 2011;20(6):846-859. doi:10.1007/s00586-010-1577-5
6. Youssef JA, Orndorff DO, Patty CA, et al. Current status of adult spinal deformity. Global Spine J. 2013;3(1):51-62. doi:10.1055/s-0032-1326950
7. Cho W, Cho SK, Wu C. The biomechanics of pedicle screw-based instrumentation. J Bone Joint Surg Br. 2010;92(8):1061-1065. doi:10.1302/0301-620X.92B8.24237
8. Christodoulou E, Chinthakunta S, Reddy D, et al. Axial pullout strength comparison of different screw designs: fenestrated screw, dual outer diameter screw and standard pedicle screw. Scoliosis. 2015;10:15. doi:10.1186/s13013-015-0039-6
9. Liljenqvist UR, Halm HF, Link TM. Pedicle screw instrumentation of the thoracic spine in idiopathic scoliosis. Spine (Phila Pa 1976). 1997;22(19):2239-2245. doi:10.1097/00007632-199710010-00008
10. Allen BL Jr, Ferguson RL. The Galveston technique for L rod instrumentation of the scoliotic spine. Spine (Phila Pa 1976). 1982;7(3):276-284. doi:10.1097/00007632-198205000-00014
11. Perna F, Borghi R, Pilla F, Stefanini N, Mazzotti A, Chehrassan M. Pedicle screw insertion techniques: an update and review of the literature. Musculoskelet Surg. 2016;100(3):165-169. doi:10.1007/s12306-016-0438-8
12. Liebschner MA, Rosenberg WS, Keaveny TM. Effects of bone cement volume and distribution on vertebral stiffness after vertebroplasty. Spine (Phila Pa 1976). 2001;26(14):1547-1554. doi:10.1097/00007632-200107150-00009
13. Rajasekaran S, Vidyadhara S, Ramesh P, Shetty AP. Randomized clinical study to compare the accuracy of navigated and non-navigated thoracic pedicle screws in deformity correction surgeries. Spine (Phila Pa 1976). 2007;32(2):E56-E64. doi:10.1097/01.brs.0000252094.64857.ab
14. Tian NF, Xu HZ. Image-guided pedicle screw insertion accuracy: a meta-analysis. Int Orthop. 2009;33(4):895-903. doi:10.1007/s00264-009-0792-3

15. Phan K, Rao PJ, Mobbs RJ. Percutaneous versus open pedicle screw fixation for treatment of thoracolumbar fractures: Systematic review and meta-analysis of comparative studies. Clin Neurol Neurosurg. 2015;135:85-92. doi:10.1016/j.clineuro.2015.05.016
16. Wang J, Zhou Y, Zhang ZF, Li CQ, Zheng WJ, Liu J. Comparison of one-level minimally invasive and open transforaminal lumbar interbody fusion in degenerative and isthmic spondylolisthesis grades 1 and 2. Eur Spine J. 2010;19(10):1780-1784. doi:10.1007/s00586-010-1404-z
17. Santoni BG, Hynes RA, McGilvray KC, et al. Cortical bone trajectory for lumbar pedicle screws. Spine J. 2009;9(5):366-373. doi:10.1016/j.spinee.2008.07.008
18. Ahn Y, Lee SH, Park WM, Lee HY, Shin SW, Kang HY. Percutaneous endoscopic lumbar discectomy for recurrent disc herniation: surgical technique, outcome, and prognostic factors of 43 consecutive cases. Spine (Phila Pa 1976). 2004;29(16):E326-E332. doi:10.1097/01.brs.0000134591.32462.98
19. Kim YJ, Lenke LG, Cheh G, Riew KD. Evaluation of pedicle screw placement in the deformed spine using intraoperative plain radiographs: a comparison with computerized tomography. Spine (Phila Pa 1976). 2005;30(18):2084-2088. doi:10.1097/01.brs.0000178818.92105.ec
20. Wang MY, Mummaneni PV. Minimally invasive surgery for thoracolumbar spinal deformity: initial clinical experience with clinical and radiographic outcomes. Neurosurg Focus. 2010;28(3):E9. doi:10.3171/2010.1.FOCUS09286
21. Meyer B, Thomé C, Vajkoczy P, et al. Lumbar dynamic pedicle-based stabilization versus fusion in degenerative disease: a multicenter, double-blind, prospective, randomized controlled trial. J Neurosurg Spine. 2022;1-10. doi:10.3171/2022.2.SPINE21525
22. Xie Q, Zhang J, Lu F, Wu H, Chen Z, Jian F. Minimally invasive versus open Transforaminal lumbar Interbody fusion in obese patients: a meta-analysis. BMC Musculoskelet Disord. 2018;19(1):15. Published 2018 Jan 17. doi:10.1186/s12891-018-1937-6
23. Huang J, Li Y, Huang L. Spine surgical robotics: review of the current application and disadvantages for future perspectives. J Robot Surg. 2020;14(1):11-16. doi:10.1007/s11701-019-00983-6
24. Singh V, Mahajan R, Das K, Chhabra HS, Rustagi T. Surgical Trend Analysis for Use of Cement Augmented Pedicle Screws in Osteoporosis of Spine: A Systematic Review (2000-2017). Global Spine J. 2019;9(7):783-795. doi:10.1177/2192568218801570
25. Feng Q, Zhang Z, Wang D, Feng J. Comparing the efficacy and safety of cement-augmented fenestrated pedicle screws and conventional pedicle screw in surgery for spinal metastases: a retrospective comparative cohort study. Transl Cancer Res. 2022;11(12):4397-4408. doi:10.21037/tcr-22-2631
26. Kahaer A, Zhou Z, Maitirouzi J, et al. Biomechanical Investigation of the Posterior Pedicle Screw Fixation System at Level L4-L5 Lumbar Segment with Traditional and Cortical Trajectories: A Finite Element Study. J Healthc Eng. 2022;2022:4826507. doi:10.1155/2022/4826507
27. Matsukawa K, Yato Y, Imabayashi H, Hosogane N, Asazuma T, Nemoto K. Biomechanical evaluation of the fixation strength of lumbar pedicle screws using cortical bone trajectory: a finite element study. J Neurosurg Spine. 2015;23(4):471-478. doi:10.3171/2015.1.SPINE141103
28. Liu D, Zhang XJ, Liao DF, et al. Biomechanical Comparison of Pedicle Screw Augmented with Different Volumes of Polymethylmethacrylate in Osteoporotic and Severely Osteoporotic Synthetic Bone Blocks in Primary Implantation: An Experimental Study. Biomed Res Int. 2016;2016:9627504. doi:10.1155/2016/9627504
29. Chen HC, Wu JL, Huang SC, et al. Biomechanical evaluation of a novel pedicle screw-based interspinous spacer: A finite element analysis. Med Eng Phys. 2017;46:27-32. doi:10.1016/j.medengphy.2017.05.004
30. Lonjon N, Chan-Seng E, Costalat V, Bonnafoux B, Vassal M, Boetto J. Robot-assisted spine surgery: feasibility study through a prospective case-matched analysis. Eur Spine J. 2016;25(3):947-955. doi:10.1007/s00586-015-3758-8
31. Lee NJ, Leung E, Buchanan IA, et al. A multicenter study of the 5-year trends in robot-assisted spine surgery outcomes and complications. J Spine Surg. 2022;8(1):9-20. doi:10.21037/jss-21-102
32. McCloskey K, Turlip R, Ahmad HS, Ghenbot YG, Chauhan D, Yoon JW. Virtual and Augmented Reality in Spine Surgery: A Systematic Review. World Neurosurg. 2023;173:96-107. doi:10.1016/j.wneu.2023.02.068
33. Burström G, Persson O, Edström E, Elmi-Terander A. Augmented reality navigation in spine surgery: a systematic review. Acta Neurochir (Wien). 2021;163(3):843-852. doi:10.1007/s00701-021-04708-3
34. Tian F, Tu LY, Gu WF, et al. Percutaneous versus open pedicle screw instrumentation in treatment of thoracic and lumbar spine fractures: A systematic review and meta-analysis. Medicine (Baltimore). 2018;97(41): e12535. doi:10.1097/MD.0000000000012535
35. Xu W, Zhang X, Ke T, Cai H, Gao X. 3D printing-assisted preoperative plan of pedicle screw placement for middle-upper thoracic trauma: a cohort study. BMC Musculoskelet Disord. 2017;18(1):348. doi:10.1186/s12891-017-1703-1
36. Lee TJ, Thomas AA, Grandhi NR, et al. Cost-effectiveness Applications of Patient-reported Outcome Measures (PROMs) in Spine Surgery. Clin Spine Surg. 2020;33(4):140-145. doi:10.1097/BSD.0000000000000982
37. Yang P, Chen K, Zhang K, Sun J, Yang H, Mao H. Percutaneous short-segment pedicle instrumentation assisted with O-arm navigation in the treatment of thoracolumbar burst fractures. J Orthop Translat. 2019;21:1-7. doi:10.1016/j.jot.2019.11.002.