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Original Article

Development Status of Closed Sacroiliac Screw in the Treatment for Sacroiliac Joint Complex Injury

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Abstract:
The complex of the sacroiliac joint constitutes a bony ligamentous structure located posteriorly within the pelvic ring, which incorporates the ilium, sacrum, sacroiliac joint and adjacent ligaments, such as the sacrospinous and sacrotuberous ligaments, together with the pelvic floor muscles and fascia. This complex serves as a crucial pathway for load transfer in the lower extremities, contributing approximately 60% to the overall functionality of the pelvis. Injuries affecting the sacroiliac joint complex account for a notable proportion of pelvic fractures and often lead to vascular and nerve injuries. Presently, various treatment modalities are available for addressing sacroiliac joint complex injuries, with internal fixation being the most widely favored approach. The current article aims to summarize the latest research advancements in the closed sacroiliac screw management of sacroiliac joint complex injuries.
Keywords: sacroiliac joint; injury; sacroiliac screw;surgical treatment.

1. Introduction

1. Anatomy and Biomechanical Characteristics of the Sacroiliac Joint Complex

The sacroiliac joint (SIJ) is recognized as the largest axial spinal joint in human anatomy, allowing limited degrees of rotational and translational movement [1]. The joint is primarily composed of fibrocartilage rather than hyaline cartilage and is reinforced by several ligaments, including the anterior and posterior sacroiliac ligaments, sacrospinous ligament, sacrotuberous ligament, and interosseous ligament. Muscles such as gluteus maximus, gluteus medius, piriformis, biceps femoris, and latissimus dorsi also contribute to its support, connecting through the thoracolumbar fascia and the erect spine [1]. The sacroiliac joint is innervated by nerves including the lumbosacral trunk nerve, superior gluteal nerve, and obturator nerve, which are susceptible to injury following trauma to the joint. Serving as part of the posterior pelvic ring, the sacroiliac joint is crucial for the maintenance of approximately 60% of the overall stability of the pelvis [2,3]. This joint plays a vital role in sustaining the stability and weight-bearing capacity of the upper body. The fibrous composition and rigidity of the sacroiliac joint complex restrict excessive movement during activities, primarily functioning to absorb multidirectional forces. While the clinically and experimentally observed movement is minimal, the morphological features present underscore the joint's significance as a load distribution zone for both the pelvis (horizontally) and the lumbosacral transition, as well as the lower limbs[4,5]. Due to the inherently weak bony stability of the sacroiliac joint, the cartilaginous and ligamentous structures of the posterior pelvic ring are essential for maintaining its stability. Utilizing CT data from the human pelvis, Yang Jiajing et al.[6] developed a three-dimensional finite element model of the pelvis in both seated and standing positions, incorporating the sacrum, ilium, coccyx, and six ligaments (sacroiliac ligament, sacrospinous

ligament, sacrotuberous ligament, inguinal ligament, suprapubic ligament, and pubic arch ligament). A vertical load of 600 N was applied to the upper surface of the sacrum to evaluate stress and displacement distribution within the pelvis and sacral joints. The findings indicated that ligamentous damage resulted in a significant increase in displacement of the sacrum and ilium in both standing and seated positions. Consequently, the components of the sacroiliac joint complex are interdependent and operate as a unified entity. The compromise of any single component within this complex adversely affects the structural integrity and overall functionality of the pelvis.

2. Advancements in the Surgical Treatment of Sacroiliac Joint Complex Injury

The Tile classification of pelvic fractures [7] includes several specific types: Type A fractures are characterized by their stability, exhibiting minimal displacement and maintaining the integrity of the pelvic ring. Within this category, Type A1 denotes injuries where the pelvic ring remains intact, including avulsion fractures of the anterior superior and inferior iliac spines, isolated fractures of the ischial tuberosity, and iliac wing fractures. Conversely, Type A2 involves ruptures of the pelvic ring that, despite being non-displaced, still retain their stability.Type B fractures indicate a scenario of rotational instability while preserving vertical stability. Specifically, Type B1 entails an 'open book' injury, which arises from fractures at the pubic symphysis due to external rotational forces, yet maintains vertical stability. This type is further categorized into three grades: Grade I, with pubic symphysis displacement of less than 2.5 cm and an intact posterior ring; Grade II, where displacement surpasses 2.5 cm, leading to the rupture of one sacrospinous ligament and anterior sacroiliac ligament; and Grade III, where displacement also exceeds 2.5 cm but results in ruptures of both sacrospinous and anterior sacroiliac ligaments. Type B2 represents a close book injury, characterized by pelvic ring damage confined to one side. The anterior pelvic ring injuries predominantly involve fractures of the upper and lower pubic bones, while posterior injuries primarily affect the sacroiliac joint complexes, including specific subtypes such as pubic symphysis interlocking and oblique fractures. Type B3, identified as a bucket handle injury, features contralateral pelvic ring injuries, with anterior injuries primarily comprising upper and lower pubic ramus fractures, and posterior injuries mainly involving the sacroiliac joint complex, with a notable subtype consisting of fractures across all four pubic rami.Type C fractures denote both rotational and vertical instability. Type C1 specifically refers to unilateral injuries of the sacroiliac joint complex, accompanied by damage to the sacrospinous and sacrotuberous ligaments. Type C2 involves bilateral injuries to the sacroiliac joint complex along with similar ligamentous injuries, while Type C3 is characterized by a rupture of the pelvic ring coupled with an acetabular fracture. Generally, surgical intervention is seldom required for Type A fractures unless in particular circumstances. For Type B1 injuries, the need for special stability is usually absent when pubic symphysis displacement remains under 2.5 cm. However, if the displacement exceeds this threshold and one or both sacrospinous and anterior sacroiliac ligaments are ruptured, the use of an external fixator is recommended barring the necessity for abdominal surgery. Most Type B2 injuries typically do not necessitate surgical treatment; however, surgical intervention may be indicated for Type B3 injuries if there is a discrepancy of over 1.5 cm between the lower limbs or if significant pelvic deformity is present[7]. Type C fractures, exhibiting both rotational and vertical instability, generally require surgical treatment[7].Traditional surgical approaches for managing injuries to the sacroiliac joint complex include pelvic external fixation, fixation via anterior or posterior plates, posterior sacral rod fixation, and universal spinal internal fixation. With advancements in research pertaining to sacroiliac joint injuries, the majority of these cases are now stabilized through the application of sacroiliac screws. A meta-analysis conducted by Chul-Ho Kim et al.[8] involving 202 patients who underwent plate fixation and 258 patients treated with sacroiliac screw fixation compared the effectiveness of these two approaches under X-ray fluoroscopy. The findings indicated that sacroiliac screw fixation demonstrated superior results compared to plate fixation in terms of functional outcomes and imaging scores. Recent technological advancements in imaging equipment and digital

methodologies have facilitated numerous investigations into sacroiliac joint screws, encompassing techniques such as C-arm fluoroscopy, CT guidance, 3D navigation, and digital guidance.

2.1 Insertion of the sacroiliac screw using conventional X-ray fluoroscopy of the C-arm

The standard method for insertion of the sacroiliac joint screw by traditional X-ray fluoroscopy of the C arm involves obtaining preoperative pelvic anteroposterior images, in addition to visualizing both the entry and exit trajectories. These images are crucial for accurately defining the entry and exit points by adjusting the tilt angle of the C-arm apparatus. The guide needle is strategically placed at the confluence of the anterior superior iliac spine and the posterior superior iliac spine, specifically located at the medial and posterior one-third of the ilium. Upon contact with the iliac surface, the direction of the guide needle is modified on the basis of the obtained perspective images. Currently, lateral views are used to validate the optimal position of the guide needle and the depth of insertion is gauged. Subsequently, a hollow drill is advanced along the guide needle, followed by the insertion of a hollow screw. Once the screw is in place, the guide needle is removed and the fluoroscopy is repeated to verify both the position and depth of the screw. Compared to conventional open reduction methods, the deployment of sacroiliac screws under C-arm fluoroscopy to address complex sacroiliac joint injuries offers several advantages, including reduced operating durations, faster postoperative recovery, minimal blood loss, shorter hospital stays, and lower incidences of postoperative complications [9]. Wei Zhou et al.[10] conducted a comparative analysis of sacroiliac screw insertion techniques using O - arm versus C - arm fluoroscopy in the treatment of complex sacroiliac joint injuries. The findings indicated that the use of long percutaneous sacroiliac screws assisted with O arm navigation significantly reduced the intraoperative preparation time, the duration of screw placement, and fluoroscopic exposure time, while simultaneously improving the accuracy of screw placement and providing more distinct navigation images when juxtaposed with C arm navigation. However, the process of placing sacroiliac screws under C-arm fluoroscopy requires frequent imaging, resulting in increased radiation exposure for both the surgeon and the patient, thereby raising concerns regarding potential radiation-induced health hazards. Additionally, the positioning of the guide pin may lack clarity during C-arm-guided sacroiliac screw placement, which could potentially lead to vascular and nerve injuries. The conventional C-arm X-ray fluoroscopy technique for sacroiliac screw insertion is primarily suitable for cases involving sacroiliac joint dislocations that do not entail neurovascular compromise, as well as for Denis type I and II sacral fractures. Despite these limitations, C-arm fluoroscopy for sacroiliac screw placement remains a widely adopted technique in clinical settings for the management of complex sacroiliac joint injuries. It is readily performed in primary healthcare facilities, alleviating economic burdens on patients while achieving satisfactory clinical outcomes. However, this procedure demands heightened proficiency from practitioners, necessitating advanced technical skills.

2.2 CT-Guided Sacroiliac Screw Placement

CT-guided sacroiliac screw placement encompasses preoperative fracture alignment, a CT scan of the patient's pelvis, and the subsequent three-dimensional reconstruction of the imaging data. This data is then imported into MIMICS software, where drawing tools facilitate the simulation of the procedural steps and the measurement of individualized screw entry points, trajectories, and lengths. Bin Sheng et al.[11] performed a retrospective analysis that assessed the clinical effectiveness of two techniques in the treatment of posterior pelvic ring injuries: intraoperative sliding CT combined with C-arm X-ray assistance versus straightforward C-arm percutaneous screw placement. Their analysis concluded that the integration of intraoperative sliding CT and C-arm-assisted percutaneous sacroiliac joint screw placement resulted in shorter operation times, enhanced precision and safety, and a significant reduction in the incidence of secondary revisions. This approach is recognized as an effective strategy for restoring the stability of posterior pelvic ring fractures. Moreover, Zhanyu Yang et al.[12] provided a comparative evaluation of CT-assisted surgical techniques against traditional X-ray fluoroscopy methods.Intraoperative computed tomography

(CT) has been shown to diminish dislocation and functional impairment while enhancing treatment efficacy, particularly in the context of posterior pelvic ring injuries addressed through sacroiliac screw internal fixation. According to the findings of Hannah Kress et al.[13], CT-guided placement of sacroiliac screws provides effective management of intricate sacroiliac joint injuries in elderly patients. This surgical approach is characterized by its safety, simplicity, and low incidence of complications. Nevertheless, despite its numerous benefits, discrepancies exist between the surgeon's actual insertion angle and the preoperatively measured angle via CT. Continuous adjustments to the insertion angle and fluoroscopy during the procedure not only heighten the trauma associated with the insertion site but also elevate radiation exposure for both patients and healthcare providers. Moreover, the relatively high cost of CT imposes a significant economic burden on patients, and the immobility of the CT equipment can complicate its use. Additionally, conventional CT rooms often struggle to maintain aseptic conditions, resulting in less frequent application of this technology.

2.3 Sacroiliac Screw Placement Guided by 3D Navigation Technology

The utilization of three-dimensional (3D) navigation technology for sacroiliac screw placement incorporates infrared sensors to monitor surgical instruments, including tracers, guide needle trackers, positioning devices, a 3D imaging display, and a C-arm X-ray machine. The patient is positioned supine with the affected hip elevated. A tracer is securely attached to the anterior superior iliac spine on the unaffected side, followed by the installation and activation of the navigation device. The C-arm X-ray apparatus then scans the pelvis, allowing visualization of cross-sectional, coronal, sagittal, and three-dimensional pelvic structures of the sacroiliac joint on the navigation system's display. The guide needle is inserted at the intersection of the middle and posterior third of the anterior superior iliac spine and the posterior superior iliac spine. Utilizing the navigation system, the surgeon can meticulously adjust the needle's position and trajectory with the aid of a moving sleeve. Drilling commences once the simulated guide needle is confirmed to traverse the iliac bone and the S1 vertebral body while circumventing the sacral foramina and canal. Throughout the insertion, the three-dimensional imaging serves to verify that the guide needle is appropriately positioned within the sacroiliac joint segment, the sacral slope, and along the lateral border of the sacral vertebra, while also ensuring it enters the midline segment of the sacral body. Upon reaching the desired position, the perspective is assessed to ascertain the adequacy of the guide needle's length and location. Following a depth measurement, a hollow drill is advanced along the guide needle, facilitating the placement of the hollow screw.A meta-analysis conducted by R. Haveman et al.[14] involving 18 studies concluded that the accuracy of screw placement in navigation-assisted percutaneous sacroiliac screw fixation surpassed that of traditional X-ray fluoroscopy, coupled with reduced frequency and duration of fluoroscopic exposure; however, no significant differences in operation time were noted. Xi Zhijie et al.[15,16,17] compared 3D navigation-guided sacroiliac screw placement with conventional X-ray-guided methods for managing complex sacroiliac joint injuries. Their findings indicated that 3D navigation-assisted percutaneous sacroiliac screw fixation results in decreased operation times, lower radiation exposure, enhanced postoperative pelvic functionality, and reduced rates of screw resection and heterotopic ossification. Notwithstanding these advantages, it is essential to recognize that 3D navigation technology is not devoid of intrinsic errors. The positioning of the virtual guide needle may not perfectly align with that of the actual guide needle, potentially resulting in data inaccuracies and deviations in screw placement.ailure to meet the anticipated treatment outcomes may result in complications including vascular and nerve damage.

2.4 Placement of Sacroiliac Screw using a 3D Printing Guide Plate

Three-dimensional (3D) printing technology enables the creation of tactile models from computer-aided design (CAD) datasets. Depending on the method used for production, it can also be referred to as rapid prototyping, solid freeform fabrication, computer automation, or layered manufacturing. The underlying principle involves reconstructing a physical 3D model from a digital one by sequentially adding layers of material. In additive manufacturing, the machine

interprets data from a CAD drawing and deposits successive layers of liquid, powder, or solid material. These layers correspond to the virtual cross-sections of the CAD model, ultimately culminating in the desired final shape (refer to the corresponding cross-sections of the CAD model)[18]. The application of 3D printing technology is particularly beneficial in the representation of complex fractures, enabling rapid production of fracture models. Currently, this technology finds extensive use within the orthopedic field. Xuanhuang Chen and colleagues[19] conducted a study employing three-dimensional navigational printing on 13 adult pelvic specimens, facilitating sacroiliac screw placement through the use of a software-designed guide plate. Their experimental findings indicated that the implementation of the 3D printing navigational module significantly enhanced the accuracy and safety of sacroiliac screw implantation. Additionally, Wu, Zhou, and associates[20] established that when compared to conventional surgical techniques, the utilization of 3D printing template technology not only decreases the duration of the operation but also minimizes X-ray exposure during sacroiliac screw placement, thereby improving procedural safety. Mu-Rong You and collaborators[21,22] posited that the use of a software-designed guide plate for sacroiliac screw placement represents an optimal approach for addressing posterior pelvic ring injuries, aiding surgeons in mitigating surgical complexity. Nonetheless, it is important to note that 3D printing guide plate-assisted sacroiliac screw placement is primarily suited for intricate sacroiliac joint injuries characterized by minimal displacement or satisfactory fracture reduction. Achieving favorable outcomes with guide plate-assisted screw placement is contingent upon the fracture being adequately reduced. Furthermore, given the requirement for guide plate design, this technique may not be appropriate for urgent clinical situations.

2.5 Robot-Assisted Sacroiliac Screw Placement

The protocol for the deployment of a sacroiliac joint screw utilizing a surgical robot encompasses several crucial steps[23]. Initially, the TiRobot orthopedic surgical robot, which represents the inaugural generation of the Tianji® orthopedic surgical robot developed by Beijing Tianzhihang Medical Technology Co., Ltd., is interconnected with a 'C' arm X-ray machine. This assembly facilitates the insertion of a percutaneous sacroiliac joint channel screw aimed at stabilizing the posterior pelvic ring, supported by robotic navigation. Fluoroscopy is employed to verify the successful reduction of the pelvic fracture. Following this, the tracer is connected and calibrated. It is imperative to cover the robot manipulator with a sterile protective sheath and ensure that the base is linked to a calibration device. The 'C' arm X-ray machine then captures essential planar images — including those of the pelvic inlet, outlet, and lateral sacral positions — which are subsequently imported into the robot's main control computer. Within this system, the Tianzhihang orthopedic surgical robot navigation software (Beijing Tianzhihang Medical Technology Co., Ltd., China) is utilized to delineate an optimal positioning for the sacroiliac screw, effectively simulating the robot arm's movement for additional refinement. The adjusted data are employed to direct the manipulator to its intended location, culminating in the successful insertion of the cannulated screw guide needle through the attachment of the sleeve.During the procedure of inserting the guide needle, it is essential to utilize fluoroscopy in order to carefully monitor the position of the guide needle, thereby avoiding any positional deviations. Once fluoroscopy confirms that the guide needle is appropriately positioned, the depth can be accurately measured, and the hollow screw can be advanced along the guide needle. Following satisfactory positioning of the screw as verified by fluoroscopy, the guide needle is then withdrawn, and the incision is sutured. Currently, the technology for robot-assisted sacroiliac screw placement is being utilized in various hospitals. Researchers such as Zhang WenHui et al.[24] have conducted comprehensive studies evaluating the precision of sacroiliac screw placements using robotic navigation, which has been shown to offer superior accuracy compared to traditional CT-guided methods. Liu Zhi et al.[25,26] have demonstrated that robot-assisted percutaneous sacroiliac screw fixation for treating posterior pelvic ring fractures results in fewer fluoroscopy exposures, reduced adjustments of guide pins, minimized intraoperative blood loss, shortened surgical duration, and an improved rate of satisfactory nail positioning, as established through meta-analysis. Furthermore, the work of

Chunpeng Zhao and colleagues[27-32] illustrates that robot-assisted sacroiliac screw placement in cases of complex sacroiliac joint injuries significantly reduces the number of intraoperative fluoroscopic procedures, effectively lowering radiation exposure while enhancing surgical efficiency. Xiao-Dong Hao et al.[33,34] found that utilizing robotic assistance for sacroiliac screw placement in the management of sacral fragility fractures not only alleviates pain but also improves fracture healing rates, clinical outcomes, and minimizes surgical complications through minimally invasive techniques. Additionally, Chengzhi Yang et al.[35] reported that robot-assisted percutaneous fixation using cannulated screws for pelvic ring injuries with sacral variations achieves commendable accuracy and safety. In comparison to traditional surgical approaches, robotic-assisted placement of sacroiliac screws proves to be more effective for complex injuries of the sacroiliac joint while substantially reducing surgical complications. Nonetheless, the high costs associated with robotic technology present significant barriers to its widespread adoption at fundamental healthcare facilities.

Conclusion

Pelvic fractures predominantly arise from traumatic events, such as accidents or falls[27]. These fractures compromise the stability of the pelvic ring, potentially leading to damage to vital blood vessels and nerves. Posterior pelvic ring fractures account for a considerable proportion of total pelvic fractures. The sacroiliac joint complex, an integral component of the posterior pelvic ring, plays a crucial role in pelvic injuries and should not be overlooked. Technological advancements have broadened the treatment modalities available for injuries to the sacroiliac joint complex, with surgical techniques becoming increasingly refined and tailored to meet individual patient needs, often resulting in reduced operation times relative to traditional methods. The proliferation of such technologies enables primary medical institutions to perform related surgical interventions, thus shortening the learning curve and facilitating the rapid development of novice surgeons. Nonetheless, the selection of surgical techniques for managing injuries to the sacroiliac joint complex should be made based on a variety of factors to ensure the formulation of the most appropriate treatment strategy.

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