DOI: https://dx.doi.org/10.18203/issn.2455-4510.IntJResOrthop20250354

Systematic Review

Integration of advanced imaging and surgical navigation in the treatment of unstable thoracolumbar spine fractures: a systematic review of functional, neurological and postoperative outcomes

Mateo D. Fabara-Vera[1]*, Carlos M. Carrasco[2], Mayra A. A. Vargas[3], Jesús Jiménez-Sánchez[4], Rafael D. V. Gonzalez[5], Sebastián B. Barreto[6], Pedro P. P. Camarena[7], Juan F. C. Pastrana[8]

[1]Medical Department, Universidad de las Americas, Ecuador
[2]Department of Traumatology, Hospital General León (Secretaría de Salud de Guanajuato), México
[3]Medicine Department, Universidad Cooperativa De Colombia, Colombia
[4]Department of Neurosurgery, Hospital Infantil de México Federico Gómez, México
[5]Department of Medicine, Independent Investigator, Colombia
[6]Medical Department, UNISANITAS, Colombia
[7]Medical Department, Universidad Autónoma de Guadalajara, México
[8]Medical Department, Universidad el Bosque, Colombia

Received: 30 January 2025
Accepted: 05 February 2025

***Correspondence:**
Dr. Mateo D. Fabara-Vera,
E-mail: mateofabaramd@gmail.com

ABSTRACT

Advanced imaging and surgical field have improved treatment and management of unstable thoracolumbar spine fractures significantly. Its emergence is boosting surgical accuracy, efficiency and its use has increased patient recovery rate. This systematic analysis is conducted to explore how these technologies affect functional, neurological and postoperative outcomes. Our aim is to evaluate and investigate previous evidences and various studies. This systematic analysis will be based entirely on retrospective analyses, randomized controlled trials, and other systematic reviews. While conducting methodology, we assessed several factors like pedicle screw placement accuracy, surgery time, radiation exposure and noted overall patient outcomes across different navigation systems like intraoperative CT navigation (iCT-Nav), 3D navigation, and augmented reality. The primary results of this systematic review revealed pedicle screw placement accuracy was high (up to 96.9% with iCT-Nav), with fewer revision surgeries needed. 3D navigation reduced fluoroscopy time significantly ($p=0.0002$) while still maintaining accuracy and evidence confirmed these techniques also helped lower blood loss ($p<0.05$) and improved spinal alignment without adding significant time to the surgery. Evidence showed radiation exposure remained an issue with varying levels of dose-length product (DLP) but it was dependent on the complexity of the procedures. Conservative management failed in 9.2% of cases while long-segment stabilization helped prevent further vertebral fractures. After all these results, we came to a conclusion that advanced imaging and navigation technologies have revolutionized thoracolumbar fracture management because its use has improved accuracy and patient outcomes which is confirmed. These technologies are also seen to reduce the need for revision surgeries and made minimally invasive surgeries more effective and also helped stabilize the spine in the long term. The challenges linked to these procedures are radiation exposure, standardization and costs which need to be carefully handled and need attention. Future research should explore what the role of artificial intelligence is and how it can work to bring maximum outcomes while making these technologies more accessible is also critical.

Keywords: Advanced imaging, Surgical navigation, Thoracolumbar spine fractures, Unstable spine fractures, Spinal surgery, Functional outcomes, Neurological outcomes

INTRODUCTION

Unstable thoracolumbar spine fractures contain about more than 90% of all traumatic spinal injuries while it is estimated that it comes with a global incidence of 3.79 per 100,000 individuals annually which is significant challenge which increases global burden because in Europe, surgical intervention for unstable thoracolumbar spine fractures has been reported to cost approximately €31,900 per patient.[1] Result from high-energy trauma together with motor vehicle collisions (45%) falls from momentous heights (30%) and sports-related accidents (10%).[2] Impact on affected individuals is profound as nearly 40% of patients experience varying degrees of spinal cord damage while leading to functional impairments or chronic pain which can reduce quality of life.[2,3] Reports show there is high morbidity associated with these fractures so timely interventions are important to improving outcomes and preventing long-term disability.[4,5] Historically, spinal trauma assessments have focused on plain radiography and computed tomography (CT) and both provide important structural insights but have limits in soft tissue evaluation and intraoperative precision. Recent advances like intraoperative three-dimensional (3D) fluoroscopy, cone-beam CT and high-resolution magnetic resonance imaging (MRI) have greatly improved diagnostic accuracy.[5] Together with real-time surgical navigation systems, these technologies have transformed the surgical management of unstable thoracolumbar fractures.[5] Most current studies show that navigation-assisted spine surgery reduces pedicle screw malposition rates from 15% to as low as 2% which reduce the risk of iatrogenic damage and reoperation.[6,7]

Despite the promised benefits, introduction if these modern imaging and navigation systems is still being debated because of related issues like long-term clinical outcomes or its cost-effectiveness and usability. Some researchers suggested these technologies improve intraoperative efficiency and reduce radiation exposure for both patients and surgeons but definitive information about their influence on functional recovery and neurological improvement is lacking.[8] This systematic analysis will critically relevance of sophisticated imaging and surgical navigation in the treatment of unstable thoracolumbar fractures. We will emphasize on functional, neurological, and postoperative outcomes. We aim to collecting the most recent information from 2019-2025, to establish if technological improvements translate into substantial gains in patient care and recommend intriguing areas for future research.

METHODS

We have followed preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines to conduct our research systematically and identify targeted outcomes mainly integration of advanced imaging and surgical navigation in treating unstable thoracolumbar spine fractures. Databases including PubMed, Embase, Web of science, Cochrane Library, and Scopus were systematically searched for relevant literature published up to 2024. Our initially designed primary key terms are: "thoracolumbar spine fractures," "advanced imaging," "surgical navigation," "intraoperative navigation," "pedicle screw placement," "3D navigation", "CT navigation," and "functional outcomes."

Design and inclusion/exclusion criteria

Included studies of this analysis include range of methodologies like retrospective cohort studies randomized controlled trials, systematic reviews and bibliometric analyses. Other grey literature, editorials, and case studies are not considered. Critical aspect of data selection involves ensuring methodological rigor, relevance and comparability across studies. Primary inclusion criteria consist of studies which has primary outcomes about intraoperative navigation, pedicle screw placement accuracy, radiation exposure and thoracolumbar fracture management. We selected the studies utilizing CT-navigation, 2D/3D navigation and systematic reviews evaluating outcomes related to spinal surgeries are considered. This paper only papers from reputable sources while we did not extract information any information from unrecognized journals. Papers published between 2019 to 2025 are considered. Research studies were excluded based on inadequate quantifiable results while lacking methodological comparisons between navigation methods and existing without quantitative evidence. Papers published prior to 2019 are skipped, and data extraction process adopts standardized methods which fully covers significant project parameters. A comprehensive analysis includes the study authors and design type plus details about participant demographics and sample count and intervention approach and methodology combined with main results for both primary and secondary outcomes and supporting quantitative data together with author conclusions and documented biases along with identified research limitations. Research data groups are organized to enable effective comparison analysis.

Methodology for risk of bias assessment

Because the variability in included study's methodology, we decided to use CASP tool. Risk of bias assessment in CASP tool is based on various factors influencing the quality and reliability of a study. Criteria such as clarity of aims, appropriate study design, sample selection, validity and reliability of data, control of biases, statistical analysis, and ethical considerations are all raised which can be seen in Table 2. We have classified each study based on these factors into levels of bias (low, moderate, or uncertain).

Primary and secondary results

Integration of advanced imaging and surgical navigation in the treatment of unstable thoracolumbar spine fractures have shown various improvements in accuracy, surgical

efficiency and patient outcomes based on our included studies. Retrospective analysis by Hagan et al have shown 96.9% pedicle screw placement accuracy with intraoperative CT navigation (iCT-Nav) while eliminating need for revision surgeries. Secondary outcomes included a 2.64% intraoperative revision rate (37 screws and 31 patients) and quantitative data showed an odds ratio (OR) of 6.21 for lateral breaches and OR of 5.79 for anterior breaches (p<0.001).

Brunken et al have reported 3D navigation improved accuracy (92.66%) over fluoroscopy (88.08%) as fluoroscopy time is reported lower in the navigation group (p=0.0002), though no significant differences were found in radiation exposure or surgical duration. Randomized controlled trial by Zhang et al shows improved screw placement accuracy in the navigation group and intraoperative blood loss and Cobb angle correction are improved (p<0.05) while surgical duration and drainage volume remained statistically insignificant. Bourret et al has also reported radiation exposure data: dose-length product (DLP) for standard deviation (SD) was 1175 mGy·cm and degenerative disease (DD) was 762.74 mGy·cm while vertebral fractures (VF) were 649.36 mGy·cm. Another primary outcome by Tan et al show conservative management failure rate of 9.2% (95% CI: 4.5-13.9%). Spiegl et al reported an Oswestry disability index (ODI) score of 31.3±24.7, sagittal loss of 5.1°±4.0, and a 35.3% sequential vertebral fracture rate with reported significant p value (0.03) for fractures. Comprehensive results by Heydar et al and González-González et al have shown augmented reality's role with the most cited article receiving 733 citations (average 59.27 citations/year).

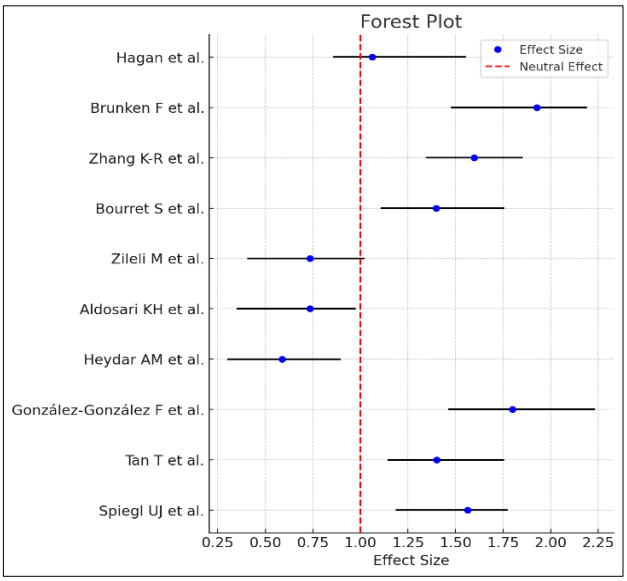

Figure 1: Forest plot.

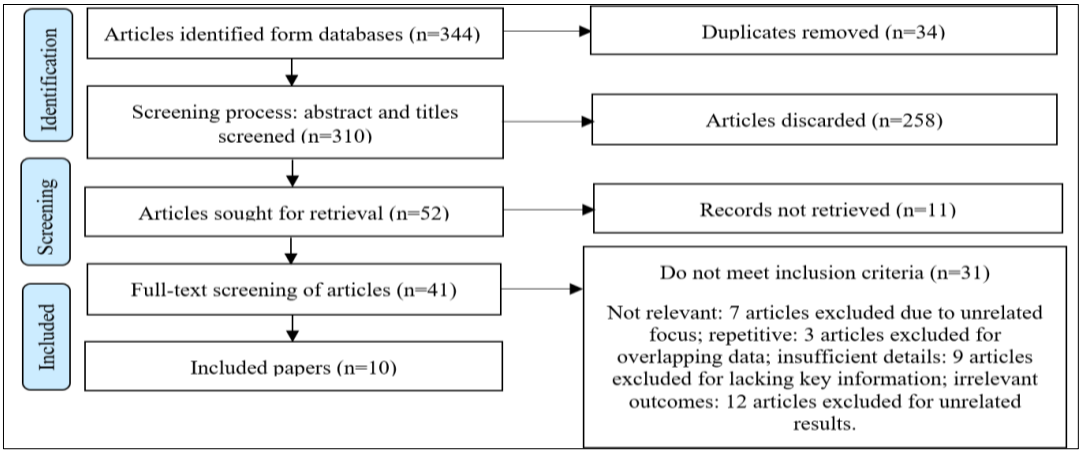

Figure 2: PRISMA flow chart.

Table 1: Primary and secondary keywords, MeSH terms, and boolean search strategy.

Primary keywords	Secondary keywords	MeSH terms	Boolean string
Thoracolumbar fracture	Spine surgery	"Spinal fractures"[MeSH]	"Thoracolumbar fractures" OR "unstable spine fractures" AND "advanced imaging" OR "surgical navigation"
Surgical navigation	Augmented reality	"Image-guided surgery"[MeSH]	"Spinal navigation" OR "O-arm CT" AND "neurological outcome" OR "functional recovery"
O-arm CT	3D imaging	"Tomography, X-ray computed"[MeSH]	"3D imaging" OR "CT-guided surgery" AND "postoperative outcome" OR "complication rates"
Neurological recovery	Postoperative complications	"Spinal cord injuries"[MeSH]	"Neurological recovery" OR "ASIA score" AND "surgical outcomes" OR "reoperation rates"

Table 2: CASP risk of bias assessment.

Study	Clear statement of aims	Appro-priate study design	Sample size and selection	Validity and reli-ability of data	Bias contr-ol	Statis-tical analy-sis	Results and findin-gs	Ethical conside-rations	Bias level
Hagan et al[9]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Brunken et al[10]	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Moderate
Zhang et al[11]	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Bourret et al[12]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low-moderate
Zileli et al[13]	Yes	Yes	Uncertain	Yes	Yes	Yes	Yes	Yes	Low
Aldosari et al[14]	Yes	Yes	Yes	Uncertain	Yes	Yes	Yes	Yes	Low-moderate
Heydar et al[15]	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Moderate
González-González et al[16]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Tan et al[17]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Spiegl et al[18]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low

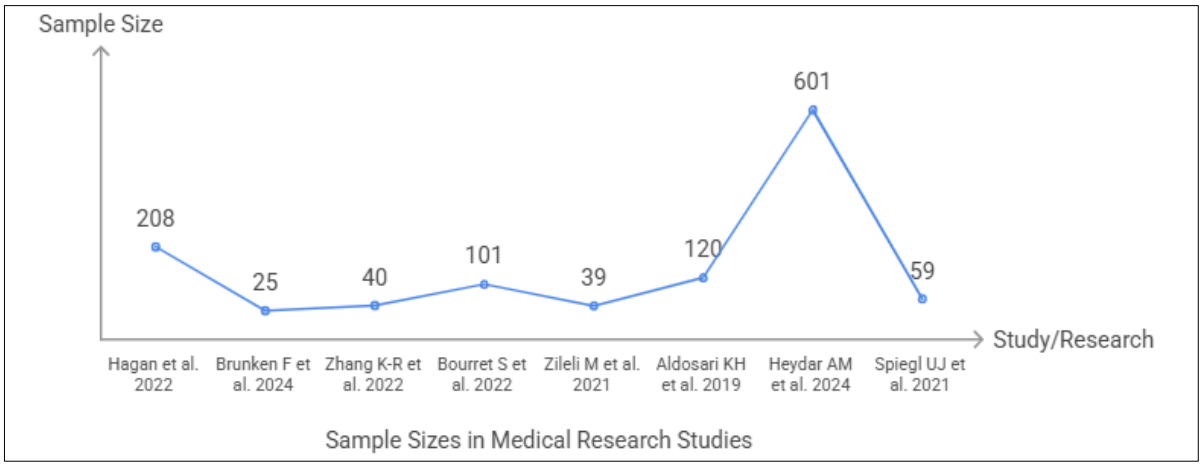

Figure 3: Sample sizes in medical research studies.

Table 3: Study details.

Author(s)	Year	Study design	Population characteristics	Sample size/range	Duration/follow-up
Hagan et al[9]	2022	Retrospective single-center analysis	Patients undergoing iCT-Nav pedicle screw placement	208 patients, 1400 screws	2015–2017
Brunken et al[10]	2024	Single-center, comparative study	Patients with traumatic thoracolumbar junction fractures	25 patients per group	Not specified
Zhang et al[11]	2022	Randomized controlled trial	Patients undergoing anterior approach thoracolumbar surgery	40 patients (navigation versus control)	May 2018 to August 2019
Bourret et al[12]	2022	Retrospective cohort study	Patients undergoing CT-navigated spine surgery	101 patients	No follow-up mentioned
Zileli et al[13]	2021	Systematic review and consensus meeting	Studies on thoracolumbar spine fractures and trauma	39 studies reviewed	2010–2020
Aldosari et al[14]	2019	Cross-sectional study	Young adults, adolescents, mostly male (84.1%)	120 patients	Follow-up from triage to discharge

Continued.

Author(s)	Year	Study design	Population characteristics	Sample size/range	Duration/follow-up
Heydar et al[15]	2024	Comprehensive literature review	Spine surgery patients (MIS, tumor resection)	Not applicable	Not applicable
González-González et al[16]	2024	Bibliometric analysis	Spine surgery articles on intraoperative navigation	100 most cited articles	1995–2019
Tan et al[17]	2022	Systematic review and meta-analysis	Neurologically intact patients with stable thoracolumbar burst fractures	601 patients (16 studies)	Not specified
Spiegl et al[18]	2021	Retrospective cohort study	Elderly patients (≥65 years) with unstable midthoracic fractures	59 patients	Mean follow-up: 60 months

Table 4: Intervention and methodology.

Author(s)	Intervention	Methodology
Hagan et al[9]	iCT-Nav-assisted pedicle screw placement	Accuracy assessed using a 2-mm incremental grading system
Brunken et al[10]	3D-navigated versus fluoroscopy-guided percutaneous pedicle screw placement	Accuracy assessed with postoperative CT using Gertzbein-Robbins classification
Zhang et al[11]	2D-navigation-guided versus non-navigation-guided vertebral screw placement	Clinical and radiological evaluations preoperatively, postoperatively, and at final follow-up
Bourret et al[12]	Intraoperative CT navigation in spine surgery	Comparison of radiation dose and number of CT scans
Zileli et al[13]	Literature review and expert consensus meetings	Systematic review, Delphi method, consensus voting
Aldosari et al[14]	Conservative and surgical management of traumatic spinal injuries	Clinical notes analysis, inclusion/exclusion criteria, anonymous data collection
Heydar et al[15]	Navigation systems in lumbar spine surgeries	Literature review of peer-reviewed journals, clinical trials, case studies
González-González et al[16]	Intraoperative image-guided navigation in spine surgery	Systematic search in Scopus and Google Scholar
Tan et al[17]	Conservative management, surgical fixation for failure cases	PRISMA-guided systematic review, pooled analysis
Spiegl et al[18]	Posterior stabilization (short-segmental versus long-segmental)	Evaluation of clinical outcomes, trauma mechanism, and radiographic loss

Table 5: Outcomes and findings.

Author(s)	Primary outcomes	Secondary outcomes	Quantitative data	Key takeaways
Hagan et al[9]	96.9% accuracy, 0 revision surgeries	2.64% intraoperative revisions (37 screws, 31 patients)	OR 6.21 (lateral breach), OR 5.79 (anterior breach), p<0.001	iCT-Nav reduces revision surgery risk, improves accuracy
Brunken et al[10]	92.66% accuracy (3D-navigation), 88.08% (fluoroscopy)	Fluoroscopy time, radiation exposure, surgery duration, intraoperative complications	Fluoroscopy time significantly lower (p=0.0002)	3D-navigation increases accuracy, reduces fluoroscopy time
Zhang et al[11]	Improved screw placement accuracy	No significant difference in surgery time, drainage volume, or correction of kyphosis	Intraoperative blood loss, Cobb angle significantly improved (p<0.05)	Navigation improves screw placement, reduces intraoperative blood loss

Continued.

Author(s)	Primary outcomes	Secondary outcomes	Quantitative data	Key takeaways
Bourret et al[12]	Radiation exposure (DLP per acquisition)	Cumulative radiation dose by surgical indication	DLP: SD (1175 mGy·cm), DD (762.74 mGy·cm), VF (649.36 mGy·cm)	Complex surgeries lead to higher radiation exposure
Zileli et al[13]	Incidence and epidemiology of thoracolumbar fractures	Regional variations, trauma causes, prevention strategies	No specific p values provided	Increasing incidence in elderly and developing countries
Aldosari et al[14]	Severity of spinal fractures, neurosurgical management	Prognostic factors (GCS, blood transfusion)	66.6% conservative, 33.3% surgical management	Majority treated conservatively, young males at higher risk
Heydar et al[15]	Accuracy of implant placement, reduction in complications	Reduced operative time, decreased radiation exposure, lower reoperation rates	Not provided	Navigation improves accuracy, minimizes complications, enhances MIS
González-González et al[16]	Citation trends, article frequency by decade	Level of evidence, author affiliations, journal analysis	Most cited article: 733 citations, avg. citations/year: 59.27	Augmented reality emerging, improved evidence in recent decade
Tan et al[17]	Conservative management failure rate (9.2%)	Predictive factors (age, kyphotic angle, canal size)	Failure rate: 9.2% (95% CI: 4.5%-13.9%)	Conservative management fails in 9.2% of cases; risk factors identified
Spiegl et al[18]	ODI score (31.3±24.7), regional sagittal loss (5.1°±4.0)	Sequential vertebral fractures (35.3%)	ODI: 31.3±24.7, sagittal loss: 5.1°±4.0, p=0.03	Long-segmental stabilization reduced sequential fractures

Table 6: Study limitations.

Author(s)	Limitations/biases
Hagan et al[9]	Single-center data, retrospective design
Brunken et al[10]	No significant differences in radiation exposure, surgery time
Zhang et al[11]	No significant differences in some clinical outcomes and radiographic measures
Bourret et al[12]	Technical limitations of CT navigation lead to higher radiation doses
Zileli et al[13]	Predominance of retrospective studies, regional bias
Aldosari et al[14]	No detailed statistical analysis, potential selection bias
Heydar et al[15]	Lack of specific statistical analysis or patient data
González-González et al[16]	Articles not specifically on thoracolumbar fractures
Tan et al[17]	Limited data on surgical management in failure cases
Spiegl et al[18]	High mortality rate (21 patients, 35.6%)

DISCUSSION

Most of included papers collectively points out that advanced imaging and surgical navigation in treating unstable thoracolumbar spine fractures is beneficial. Emergence of these technologies have improved screw placement and results declared this use also reduce revision surgeries. Navigation-assisted techniques are seen to outperform traditional fluoroscopy in precision and efficiency while minimizing intraoperative complications. Medical navigation represents both an opportunity to enhance minimally invasive procedures while simultaneously decreasing patient repetition operations despite radiation exposure risks. The rising importance of augmented reality technology and navigational systems becomes clearer through systematic review research. These technologies face current challenges stemming from research methodological uncertainties and participant selection inconsistencies yet require ongoing work for developing improved treatment selection strategies. Hagan et al conducted retrospective and single-center study analyzing 208 patients who underwent iCT-Nav-assisted pedicle screw placement. Using a 2-mm grading system, results show 96.9% of 1400 screws were placed accurately, with no postoperative revision surgeries required. Intraoperative screw revision occurred in 2.64% of cases while statistical analysis revealed higher odds of high-grade breaches for lateral (OR=6.21, p<0.001) and anterior (OR=5.79, p=0.001) placements. Hagan et al have concluded iCT-Nav enhances screw placement accuracy while eliminating postoperative revision surgery risks but is important to know that single-center retrospective design might limits generalizability of findings.[9] Brunken et al also conducted a research in 2024 where they compared 3D-navigation and fluoroscopy for pedicle screw placement in traumatic thoracolumbar fractures. In results, it was clear that 3D-navigation yielded 92.66% accuracy compared to 88.08% for fluoroscopy (p=0.19).

They have also reported that fluoroscopy time was reported lower for the navigation group (p=0.0002). Radiation exposure, surgery time or intraoperative complications showed no significant differences between the two methods and thus, it is determined that 3D-navigation enhances screw placement accuracy and reduces fluoroscopy time without increasing surgery duration or radiation exposure which points out its potential benefit for thoracolumbar spine fracture surgery.[10] Another research by Zhang et al in 2022 is reported in the form of randomized controlled trial where they compared 2D-navigation-guided and non-navigation-guided screw placement in anterior thoracolumbar surgery for burst fractures. Zhang's findings show navigation group achieved more accurate screw placement and reduced intraoperative blood loss while, on the same time it improved Cobb angle measurements in the coronal plane. Both groups verified improvements in kyphosis correction but no significant differences were found in surgery time, drainage volume or other radiological measures so this study concludes that navigation enhances screw placement accuracy and or it might have a positive impact on long-term patient prognosis without potentially affecting other surgical limitations.[11] Bourret et al have retrospectively analyzed 101 patients and all these underwent CT-navigated spine surgery to evaluate patient radiation exposure. Primary results of this research show radiation dose per acquisition was similar across surgical indications (spinal deformity, degenerative disease, and vertebral fracture) but complex surgeries which were spinal deformities required more CT scans resulting in a higher cumulative radiation dose: 1175 mGy·cm versus 762.74 mGy·cm for degenerative disease and 649.36 mGy·cm for vertebral fractures. Bourret et al have concluded CT navigation is and effective tool to reduce surgical complications but there is possibility that it can increases radiation exposure when it comes to complex procedures.[12] Another systematic research by Zileli et al analyzed 39 studies on thoracolumbar spine fractures from 2010 to 2020 and this study primarily aimed to assess the incidence and epidemiology of thoracolumbar fractures and inform prevention strategies. Using the Delphi method, expert consensus was gathered revealing that thoracolumbar fractures are increasing, especially among the elderly in developed countries and due to motor vehicle accidents in developing countries. The review presents need for targeted prevention efforts and acknowledges regional differences in injury patterns, while showing importance of epidemiological data in guiding prevention strategies.[13] Aldosari et al conducted a cross-sectional study which is based on 120 Saudi patients with traumatic spinal injuries (TSIs). This study looked at severity of injuries and management measures, concluding that road traffic accidents emerged as leading cause. Majority of patients (66.6%) were treated conservatively with 33.3% undergoing surgical intervention and study discovered that TSIs mostly impacted young adults and adolescents with a higher proportion of male patients. It indicated that early management is critical to avoiding negative outcomes in cervical spine injuries. Conservative treatment was more common and early surgical intervention resulted in positive outcomes in certain cases.[14] A review of navigation systems for lumbar spine surgery was performed by Heydar et al. This review traced the progression of these techniques starting from the use of computer-assisted surgery through image-guided surgery before reaching robotic systems over the past forty years. The research confirmed that implant accurate placement depends on navigation systems which result in reduced surgical procedure complications while also decreasing the need for additional surgeries. The research methodology revealed multiple benefits including reduced surgical duration with significantly lowered exposure to radiation. Extended cost effectiveness along with surgeon education will make spinal surgery navigation essential despite ongoing studies needed to achieve the system's greatest clinical benefits.[15] González-González et al have recently in 2024, conducted bibliometric analysis of the 100 most cited articles on intraoperative image-guided navigation in spine surgery and this study analyzed trends across publication years (1995–2019) identifying key articles, authors, and evidence levels. Results revealed a peak in publications from 2010 to 2019 with significant advancements in augmented reality in spine surgery while majority of articles had clinical research and reviews with evidence grades IV-V. This research stated technological progress in navigation systems has positively impacted spine surgery increasing citation frequencies and enhancing evidence-based practices in the field.[16] Tan et al in 2022 in their systematic review and meta-analysis, have accessed failure rate of conservative management for neurologically intact thoracolumbar burst fractures and this study found a 9.2% failure rate (95% CI: 4.5-13.9%) and identified key predictive factors were: age, kyphotic angle, residual canal size, and interpedicular distance. All these identified factors help predict failure in conservative management and promote shift to surgical intervention while it is also stated that careful consideration of these factors is critical when deciding between conservative and surgical approaches while presenting need for further prospective studies on management strategies.[17] The researchers from Spiegl et al examined elderly patients (≥65 years) with unstable midthoracic spine fractures who received posterior stabilization procedures. The findings from a 60-month patient observation demonstrated long-segmental posterior stabilization resulted in fewer subsequent vertebral fractures than short-segmental stabilization (p=0.03). Among 59 elderly patients treated by posterior stabilization the survival rate was 64.4% and the mean ODI score was 31.3 showing minimal to moderate long-term disability. Researchers find that extending the extent of stabilization can lead to superior prevention outcomes for secondary vertebral fractures while death rates stay very high.[18]

CONCLUSION

After all research, it is concluded that advanced imaging and navigation technologies have revolutionized thoracolumbar fracture management. These technologies

have enhanced precision and provide detailed views, which reduce complications to improve patient outcomes. While benefits like reduced revision rates and improved accuracy are evident but challenges remain in optimizing radiation exposure and standardizing navigation techniques across diverse patient populations and these issues need to be resolved. Future research should focus on improving these technologies and pay more focus to integrate artificial intelligence use. Overall, our findings show paradigm shift in spine surgery where precision and safety have taken precedence. Navigation technologies are growing ways more efficient and less invasive operations which will lead to improved long-term outcomes for patients. Continued breakthroughs and collaborative research are critical for overcoming current limits and guaranteeing equal access to these innovations across various healthcare settings.

Funding: No funding sources
Conflict of interest: None declared
Ethical approval: Not required

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Cite this article as: Fabara-Vera MD, Carrasco CM, Vargas MAA, Jiménez-Sánchez J, Gonzalez RDV, Barreto SB, et al. Integration of advanced imaging and surgical navigation in the treatment of unstable thoracolumbar spine fractures: a systematic review of functional, neurological and postoperative outcomes. Int J Res Orthop 2025;11:381-8.