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Artificial Intelligence–Augmented Optimization of Cannulated Screw Configurations for Pauwels Type III Femoral Neck Fractures: A Critical Review of Biomechanical and Computational Approaches

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Abstract

Around 50% of the world's hip fractures are femoral neck fractures, which are projected to increase by 30% by 2025. Among these fractures, the Pauwels type III fractures are most unstable due to their steep fracture angles, resulting in high shear and rotational stresses. Despite the fact that cannulated screw fixation remains the most cost-effective and least invasive method of treatment, high rates of fixation failure in vertically oriented fractures are cause for concern. This review synthesized 2017-2025 experimental, finite element (FE), and computational studies on cannulated screw configurations and their biomechanical performance, and the preliminary orthopaedic utilization of Artificial Intelligence (AI) and Machine Learning (ML). Among the evidence supporting advanced configurations, the oblique triangular configuration arguably provides the best resistance to shear and most favorable stress convergence over the others. TiRobot and TianJi, as well as screw design and spacing, are not fully optimized to enhance the fixation relative to patient anatomy. Combination of the AI and ML will be the future where replace the slow and the computationally expensive FE analysis solvers, thereby enabling near-instantaneous parametric optimization. It will improvise the orthopaedic surgery away from empirical methods and clinically adopt biomechanical fixation methods, resulting in smart fixation and advanced orthopedic surgery.

1. Introduction

Current data suggests that over 2 million cases of hip fractures are reported every year and that this number will rise almost 30% by 2025 [1]. 50% of these cases are reported to be femoral neck fractures which has the highest morbidity and mortality [1]. These fractures become a strong concern in the field of orthopedic trauma, especially within the geriatric population due to the association with osteoporosis. However, in the younger population, these fractures can still be acquired, especially through high energy trauma in motor vehicle collisions and sports injuries. Pauwels type III femoral neck fractures are often acquired in high energy traumas. These fractures are highly complicated due to the slice of the fracture line which exceeds 50˚ to the horizontal and the plane of the fracture, these fractures are often referred to as complex fractures [1]. High amount of shear forces and high instability complicate the high-level fracture within the appropriate implant selection.

The use of cannulated screws in the treatment of Pauwel’s type III femoral neck fractures is due to the appropriate fracture stabilization and the accommodating versatility to different fractures and anatomy as well as their standard issue in multiple sizes and availability [2]. Accommodating versatility that screws within different shapes and configurations to the fastening of a fracture in multiple dimensions enables a surgeon to account the optimal stabilization in factors like the thread pattern, the diameter, and the length and also account the specific fracture. Given its straightforward, minimally invasive nature as well as its affordability, the cannulated screw fixation method can be offered by low resource healthcare facilities [3]. However, there are still higher rates of fixation failure with the implant, particularly with Pauwels type III fractures, owing to the vertically aligned fracture line that produces significant shear and rotational forces [4].

The design of the screw as well as the choice of materials affects the stability of the implant, but most importantly, it also depends on its configuration [5]. Of all options, configuration offers the most opportunity for improvement: changes to the trajectories, spacing, and triangulated design can enhance the implant's load distribution by altering the cortical engagement without increasing costs and additional devices [5][6]. In contrast, changes to the diameter of the screw or other components as well as the type of material are likely to increase costs and add complications to the surgical instruments. Therefore, the configuration of the implant should be the primary factor to consider before looking to other factor such as implant material or design.

Recent improvements in technology, especially Artificial intelligence (AI) and Machine learning (ML) are utilized in biomechanical analysis [7]-[12]. In orthopaedic research and practice, they enhance the accuracy of diagnostics, predict outcomes, and enhance the overall surgical plan predictive value. Neural networks and other AI techniques are used to automate some processes in orthopaedic surgery like detecting fractures, classifying injuries, and planning screw trajectories [13]. Their accuracy matches or exceeds that of orthopaedic surgeons. ML, which is a part of AI, includes computation and statistical techniques like Support Vector Machines (SVMs) and other deep learning techniques to understand and analyse complex clinical and biomechanical data. These algorithms automate the preoperative planning process, predict surgical outcomes and complications, and optimize the position of surgical implants. AI and ML improve predictive analytics, assist personalized surgical planning, improve clinical decision making and predict outcomes, and reduce fixation failure rates in complex fractures like Pauwels type III.

One of the most defining features of AI-assisted fixation in modern AI-assisted skeletal fixation is the ability to employ intelligent optimization algorithms to devise individualized fixation patterns in accordance with defined biomechanical goals. This critical review traced the development of cannulated screw fixation configuration in Pauwels type III fracture and examines the various ways AI and ML influence biomechanics, design optimization, and the clinical application. This work consolidates findings from experimental, finite-element, and computational studies, identifies emerging gaps, and articulates pathways for the AI integration of conventional biomechanics and agile advanced modelling. This would allow the first AI-driven personalized, evidence-based, and dynamic fixation strategies to be developed for complex femoral neck fractures such as Pauwels type III.

Nomenclature

AI	Artificial Intelligence
ML	Machine Learning
DL	Deep Learning

2. Methodology of Review

Systematic literature search was performed for peer-reviewed papers published in Scopus, Web of Science, PubMed, and IEEE Xplore within the 2017-2025 period to reflect the recent growth of machine learning applications in orthopedics. Search strategy consisted of the application of Boolean operators in addition to the usage of very specific mesh terms regarding medicine and engineering: ("cannulated screw" OR "screw configuration") AND ("femoral neck fracture" AND "Pauwels type III") AND ("finite element analysis" OR "FEA") AND ("artificial intelligence" OR "machine learning" OR "optimization"). As an additional measure, backward and forward citation chasing was conducted manually for the identified key studies.

To ensure thematic consistency with the crucial scope of this review, studies were screened against three unique selection criteria: (1) anatomical emphasis on high-angle femoral neck fracture with higher shear risk (Pauwels type III or vertical variants greater than 50°);(2) mechanical assessment or optimization of cannulated screws' positionings, geometries, or arrangements; and (3) use of artificial intelligence, machine learning, or

Int. Journal of Integrated Engineering Vol. 18 No. 4 (2026) p. 238-254

automated computational optimization process was taken into consideration. Both standalone computational studies and hybrid experimental-computational frameworks were used in this study. Data extraction followed by critical appraisal were performed systematically across all selected studies. For each study that was selected data were extracted on the type of implant design, the optimization technique used for the computation/artificial intelligence algorithm, the mechanical/biomechanical response in terms of stability and stress transmission, as well as the clinical significance of the model in orthopaedics.

3. Result

3.1 Cannulated Screw Selection: Design, Dimensions, and Configuration

The efficacy of the implant depends on the selection of the cannulated screw. There is various type of cannulated screws is available, some are partially threaded and some fully threaded, and some come with heads and washers while others do not [14]. The selection of the implant is made based on the bone quality, fracture pattern, and anatomical constraints, and every modification satisfies a specific biomechanical requirement [15]. For instance, a screw with a threaded distal end and fully threaded shaft allows interfragmentary compression and the deep threaded shaft screws are widely used because their design allows interfragmentary compression. According to Wang et al. [16], the smooth shaft traverses the proximal fragment, while the threaded section interacts with the distal fragment, thereby approximating the fracture ends. The compression a partially threaded cannulated screw provides is important for the fracture to stabilize and heal.

The screw comes in a range of sizes, especially with diameters of 6.5 mm to 7.3 mm and lengths of 50 mm to 120 mm [17]. The ideal screw diameter depends on various factors such as the bone quality, along with the width, length, and fracture pattern of the femoral neck [18]. Apivatthakakul et al. [17] illustrated the importance of positioning the gap tip of the screw within 3 mm of the internal bone wall, achieving optimal support and reducing micromotion around the fracture. Screws should also be designed to rest 5 mm before the joint surface [17]. This protects the joint cartilage, prevents joint intrusion, and minimizes the risk of articular cartilage damage. For femoral neck fracture repair, the 16 mm and 32 mm threaded lengths of cannulated screws present a choice that must balance anatomical fitting and biomechanical stability. Liu et al. [19] described the identified region of internal compression and isolation of the fracture site for the 16 mm diameter, short-threaded screws, which engage the femoral head and aims to preserve fracture internal compression forces.

In cases of osteoporotic fracture fixation, inadequate support might lead to fixation failure. However, longer threads (32 mm) are able to augment bone contact and avoid varus collapse [19]. However, there is a risk of crossing the fracture line, which could also impede compression and thus, fracture healing in cases of shorter femoral necks [19]. Therefore, obtaining preoperative (CT or MRI) images is critical for evaluating the distance from the subchondral bone to the fracture line to ensure that the 32 mm threads are used only when the distance is more than 32 mm to avoid the complication. Patient-specific factors (bone quality, gender, and height) are also may influence thread selection [18].

As mentioned above, conventional attachment techniques use between 2 and 4 screws, which depending on the required stability, can be configured in inverted triangles, diamonds, or oblique triangles. For construction, one of the commonly used fixation techniques for femoral neck fractures is the three cannulated screws arranged in an inverted triangle. This technique is praised for its low invasiveness and preservation of the overlying soft tissues and the vascular supply of the area [20]. Yet in unstable or vertical fractures (Pauwel's type III), the sheer cannulated screws may lack the effectiveness since there is an insufficient resistance to the shear forces and consequently, fixation failure is likely to occur. To overcome that, the use of several screws arranged in an inverted triangle has been suggested to improve rotational stability and control over the distribution of the shear forces. Although the technique and fixation cost of cannulated screws is inexpensive, the effectiveness does depend on the approach taken from the surgeon, particularly the placement and alignment of screws relative to one another. Table 1 shows the ranges and dimensions of screws used in the previously cited studies.

Table 1 *Overview cannulated screw*

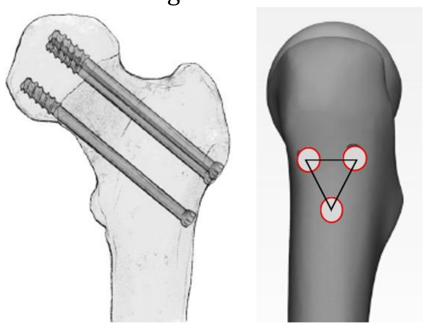
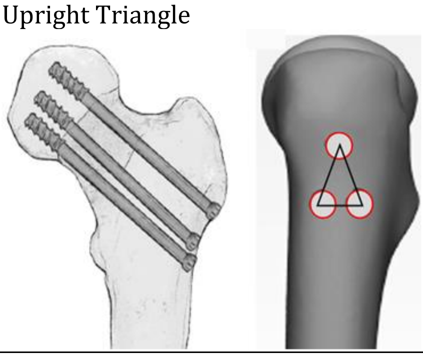
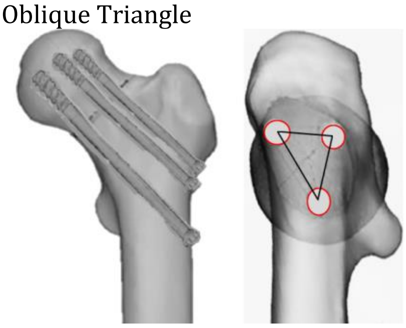
Study	Country	Study type	Age	Fracture type	Configuration	Screw type
Zhang et al. [21]	China	Experimental	Adult	50°, 60°, and 70° Pauwel's angle	Inverted triangle	Partial & fully Diameter:6.5mm Thread length:16mm
Raj et al. [2]	Malaysia	Clinical	18-60	Pauwel's & Garden	Inverted triangle	Partial Diameter: 6.5mm, Thread Length:16mm

Study	Country	Study type	Age	Fracture type	Configuration	Screw type
Lei et al. [22]	China	Simulation	18-61	Pauwel's type III	Equilateral and oblique triangle screw	Partial Diameter:6.5mm, Thread length:16mm
Zhou et al. [23]	China	Clinical	Adult	Pauwel's & Garden	Inverted triangle	Partial Diameter:6.5mm, Thread length:16mm
Jiang et al. [24]	China	Simulation and experimental	Elder	Pauwel's type III	5 varies	Partial Diameter:6.5mm, Thread length:16mm

3.2 Cannulated Screw Configurations: Biomechanical Evidence

The literature review shows in Table 2 indicates that researchers employed three primary geometric configurations: inverted triangle, oblique triangle, and upright triangle. Research primarily utilized 6.5-mm or 7.0–7.3-mm cannulated screws, with most models or cohorts concentrating on adult femoral neck fractures, frequently classified as Pauwels type III, along with a smaller group classified as type II or unspecified "femoral neck fractures.

Table 2 *Summary of three-screw cannulated configurations studied*

Screw Configuration	Screw size (mm)	Fracture Type	Age group	Country	Study
Inverted Triangle 	6.5	Pauwels type III	20-60	China	[21]
		Femoral neck fracture	Adult	Spain	[22]
			21-65	India	[23]
			Adult	Brazil	[24]
		Pauwels type II	25	India	[25]
			Adult	Thailand	[26]
		Pauwels type III	Adult	China	[15] [27] [28] [29]
	7.3	Pauwels type III	30	China	[30] [31] [32]
	7		Adult	Turkey	[33]
Upright Triangle 	6.5	Femoral neck fracture	21-65	India	[23]
			Adult	Spain	[22]
		Pauwels type II	Adult	Thailand	[26]
		Pauwels type III	Adult	China	[21] [28]
Oblique Triangle 	6.5	Pauwels type III	18-65		[27]
	7.3	Pauwels type III	Adult	China	[31] [32] [34]

Int. Journal of Integrated Engineering Vol. 18 No. 4 (2026) p. 238-254

3.2.1 Inverted Triangle Configuration

The inverted triangle configuration is the most commonly utilized method for treating femoral neck fractures. This configuration is biomechanical efficiency and supports quick surgical implementation. Three screws are aligned parallel to the axis of the femoral neck: one screw is located at the inferior calcar, while two screws are positioned superiorly (Refer to Table 2). According to Table 2, the majority of studies concentrate on the three-screw inverted triangle configuration as a direct comparator, owing to its practical application in medical practices and its mechanical stability. Multiple studies concerning adult Pauwels type III fractures demonstrate a common application of 6.5-mm cannulated screws, as reported by Belwanshi et al. [35], Jiang et al. [21], Lei et al. [27], Cui et al. [15], and Zhou et al. [29]. This configuration generally positions three screws in an inverted triangular arrangement, which improves cortical support by engaging the anterior, inferior, and posterior cortices of the femoral neck to reduce torsional and shear forces [36]. Tianye et al. [37] and Zhang et al. [31,32] utilized 7.3-mm cannulated screws arranged in an inverted-triangle configuration to examine Pauwels type III femoral neck fractures (FNFs) on Asian anthropometric femur models. The investigations indicate that a 7.3-mm cannulated screw may be suitable for certain Asian femur bone model, provided that inter-screw spacing, tip–subchondral distance, and calcar purchase remain constant, exhibiting stiffness and failure metrics that are equivalent to or superior to those of 6.5-mm constructs [37].

3.2.2 Upright Triangle Configuration

In contrast to the conventional inverted triangle design, which typically employs two screws in a superior position and one in an inferior position, an upright triangle configuration intentionally alters the anatomical positioning of these screws. A particular series of studies has examined the use of upright triangle screw designs for the repair of femoral neck fractures in adults, often with 6.5-mm cannulated screws. Table 2 indicates that the number of research utilizing the upright triangle arrangement is fewer in comparison to the inverted triangle layout. Li et al. [28] and Jiang et al. [21] studied three-cannulated-screw constructs on adult femoral-neck models with Pauwels type III high-shear, vertically oriented, and upper femoral-neck fractures.

Alternatively, Chantarapanich et al. [26] studied the same screw design on fractures classified under Pauwels type II, broadening the anatomical-mechanical rationale with fractures of reduced verticality. Adult patient cohorts have documented the clinical application of the three-cannulated-screw design. Trikha et al. [23] aimed universal femoral neck fractures using upright triangular three-screw constructs. There are also clinical studies. Muñoz et al. [22] reviewed 53 adults treated from 2015 to 2022 with three screws arranged either into upright triangular or inverted-triangular configurations and showed no significant differences in functional and mechanical outcomes while documenting a total of nine complications; within this cohort, 22 of 53 cases had a triangular configuration. In Pauwels type III femoral neck fractures, the upright triangle consistently demonstrates worse effectiveness relative to the inverted triangle. The clinical trial demonstrates no substantial difference in mechanical stability when using the upright triangle form.

3.2.3 Oblique Triangle Configuration

The oblique triangle configuration is a progressive adaptation of the traditional inverted-triangle baseline, designed to enhance the spatial distribution of three screws while preserving vascular safety corridors. Unlike earlier designs, including inverted equilateral or maximum-area inverted isosceles triangles, the oblique triangle configuration deliberately tilts the triangular footprint to correspond with the torsion, elliptical isthmus of the femoral neck, seeking to maximize the enclosed area/perimeter and improve cortical purchase reliability [32]. The majority of current studies are limited to computational finite element analyses and mechanical testing on synthetic models, with few clinical series employing an OTC oblique triangle configuration protocol; consequently, real-world applications, workflows, and complication profiles are unreliable at this level [28][31]. All studies employed this arrangement for Pauwels type III femoral neck fractures in adults [27][31][32][34]. The research conducted by Zhang et al. [31][32][34] utilized a screw diameter of 7.3 mm, whereas Lei et al. [27] adopted a 6.5 mm cannulated screw for the adult population.

All studies carried out in Asia, particularly in China, utilized the Asian anthropometric femur bone model. Zhang et al. [31] performed an experimental biomechanical investigation utilizing synthetic femora modeled as Pauwels type III fractures to assess the mechanical stability characteristics of the oblique-triangle configuration. Research indicated that the arrangement of oblique triangles has better mechanical performance as compared to the configuration of inverted triangles. Under static loading conditions, the differences recorded between the two constructions, as far as axial stiffness and ultimate load, were significant. Under cyclic loading conditions, the oblique triangle configuration under cycle stresses showed less displacement of the femoral head as compared to the inverted triangle arrangement. Research suggests that oblique triangles configuration may decrease the likelihood of fixation failure and, consequently, reduce the rate of reoperation in younger and middle-aged adults.

This particular arrangement performs better than the layout consisting of inverted triangles. However, this has not been the subject of clinical research as much as the configurations of inverted triangles.

3.2.4 Other Configurations

Multiple configurations is a part of configuration than others where included screw or plate fixation, cross screw fixation, or novel construction methods have been used to stabilize adult Pauwels type III fractures. Most of the studies used the 6.5mm screw which allowed for the use of an additional screw or cross-screw fixation. The term cross fixation refers to the arrangement of the screw in a cross-fixation design as shown in (Figure 1) to improve stability [21][29]. Cross screw insertion, as demonstrated in Jiang's clinical trial [21], effectively reduces the rate of femoral neck shortening (8.3% vs 28.9%) when compared to the inverted triangle configuration. A cross-fixation design compared to an inverted triangle design also demonstrated lower rates of non-union and avascular necrosis.

Additionally, simulation studies examine the repair of Pauwels type III fractures using the inverted triangle design with cannulated screws, supplemented by an additional medial plate (refer to Figure 2) [30][31]. Giordano et al. [24] and Tianye et al. [37] argue that adding a medial plate to the cannulated screw can lessen torsional and shear stress while maintaining axial compressive stress at the fracture site. The medial support plate effectively mitigates the shearing force linked to Pauwels III femoral neck fractures and significantly improves resistance to maximal loading in Pauwels type III fractures. Şensöz et al. [33] incorporated an additional configuration of an inverted triangle arrangement with the 7.0mm cannulated screw on the Turkish femur bone model. Nevertheless, the study of Belwanshi et al. [35] in India used 6.5mm 4 and 5 cannulated screws to stabilize Pauwels type III fractures. The research demonstrates that the incorporation of cannulated screws diminishes the tension and deformation experienced in the femoral bone model. Several investigations have transposed or rotated the traditional three-screw triangle, particularly the shifted variant, to augment calcar engagement or bolster posterior column stability [15] [38]. These hybrid and multi-screw methodologies collectively demonstrate a pragmatic design principle: provide focused reinforcement in areas of significant shear and rotation, while customizing the quantity and placement of implants to suit fracture morphology and the existing anatomical pathways.

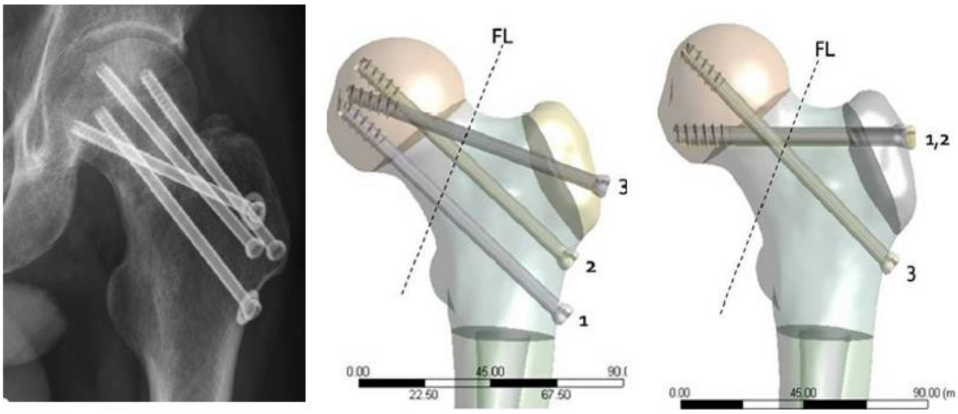


Fig. 1 *Cross cannulated screw configuration [21][29]*

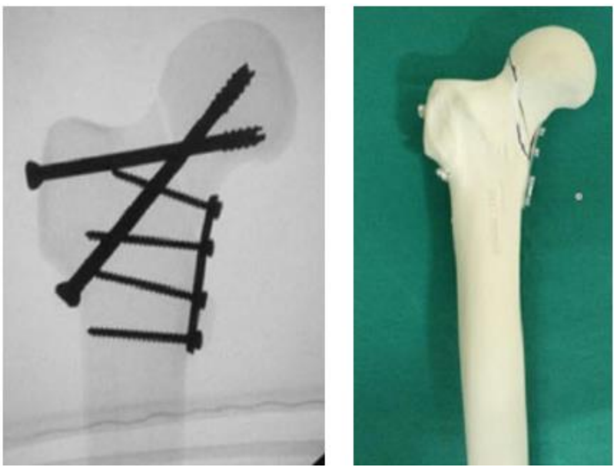


Fig. 2 *Cannulated screw with the medial plate fixation [30][31]*

Int. Journal of Integrated Engineering Vol. 18 No. 4 (2026) p. 238-254

3.3 Integration of Artificial Intelligence (AI) and Machine Learning (ML) in Orthopedic

AI and ML are applied in several fields, including healthcare, where they help treat and detect bone fractures. The term Artificial Intelligence describes the technology's ability to mirror human cognitive functions, aiming to design systems that self-learn from data and autonomously improve with time without needing reprogramming. Machine Learning, the subset of Artificial Intelligence, emphasizes algorithms that enable systems to learn from data in order to predict or classify future data. It involves neural networks, decision trees, and various clustering techniques. Each of these different types of data analysis and predictive modeling algorithms is designed for specific applications [39][40]. AI/ML technologies applied to orthopedic surgery and bone fractures stem from their potential to improve the precision of diagnoses and the outcomes of treatment. Developments in AI technologies provide valuable assistance for diagnosing scaphoid fractures, which are often missed during regular evaluations. It also shown to increase detection rates of such fractures, enhancing and expediting decision-making regarding patient care management [41].

Moreover, AI evaluation of patient specific features, including comorbidities, and specific injury patterns, presents an opportunity to further optimize tailored fracture management and operative decision making. Evaluating large datasets will empower orthopaedic surgeons with the data necessary to determine when to operate and when to provide non-operative management [42]. While AI has remarkable potential, it should be emphasized that the adoption of such technologies in clinical practice will be limited if they are not carefully and thoughtfully integrated. This is precisely the reason that the subtleties of each situation will require the intervention of a clinician in order to customize the most appropriate management [42].

3.4 Global and Temporal Distribution of AI Research in Orthopedics

Between 2017 and 2025, Figure 3 illustrate the publications at the intersection of artificial intelligence (AI), machine learning (ML), and orthopedics have come from 15 countries. Of these, six were Asian countries (China, India, South Korea, Japan, Indonesia, and Malaysia, and Singapore and Thailand), with the rest spanning North America, Europe, and South America. The United States leads the globe with an approximate output of 220 documents, and well ahead of the next major contributors (the United Kingdom, China, and India) with roughly 40-50 publications each. The European countries Italy, Germany, Switzerland, and the United Kingdom add to the output, signifying active participation from these countries and indicating strong collaboration beyond Europe.
In the temporal sense, the volume of publications relating to research in AI and orthopedics suggests an ever-increasing interest in the field. The years between 2017 and 2020 saw only slow growth in this field, with fewer than 25 papers published each year. The following year, however, took a dramatic turn, with studies published peaking at around 120 publications in 2025. This growth can be attributed to the focus on the use of AI in orthopedics during the global research expansion period. The overall data suggests that Western countries are still the largest contributors, but an emerging and increasing research output is coming from Asia, with a growing involvement in research orthopedics.

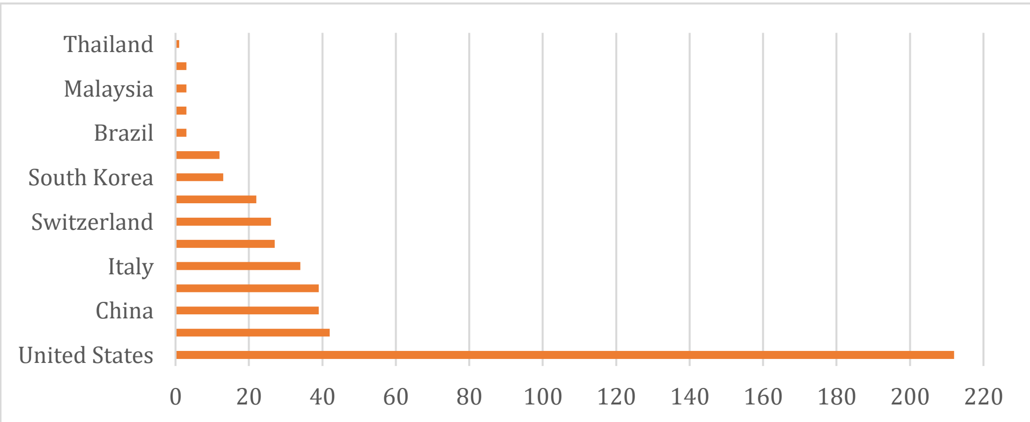


Fig. 3 *Global distribution of included studies (2017–2025). Numbers mark study counts per country: United States (n=212), United Kingdom (n=42), China (n=39), Italy (n=34), Germany (n=27),Switzerland (n=26), Canada (n=22) dominates, followed by South Korea (n=13), Japan (n=12), Brazil (n=3), Indonesia (n=3), Singapore (n=3), Malaysia (n=3) and single-country contributions from Thailand (n=1 each). The outcomes indicate that the United States dominates global research production in AI and ML applications for orthopaedics, with significant contributions from Europe and Asia*

3.5 AI Techniques Applied in Orthopedic Diagnosis and Treatment Optimization

In orthopedics, artificial intelligence (AI) frameworks are developed to fix the higher computational cost and time associated with the conventional iterative Finite Element Analysis (FEA). However, to evaluating the highly unstable fractures, like Pauwels type III fractures of the femoral neck, optimization of the fixation involves calculating complicated multi-plane shear stresses and Von Mises stress. Typically, modelling these mechanical responses under a wide range of parametric changes (e.g., variations in screw diameters, pitches, and convergence angles) requires more computation time and cost. To overcome this limitation, artificial intelligence (AI) models, including Deep Neural Network (DNN) and regression-based models, are developed using synthetic training datasets created based on initial FEA [13][43].

Once validated, these AI models act as smart solvers by predicting the stiffness, interfragmentary displacement, and mechanical failure probabilities almost instantaneously. Instead of utilizing finite difference equation solvers that come along with conventional FEA, it is now possible to carry out high-throughput geometric optimizations using predictive machine learning models like Random Forest, XGBoost, and support vector machine classifiers have been dominantly used for predictive risk assessment and forecasting outcomes associated with fractures, healing, recovery post-operative, and implants, as well as predicting implant failure [44][45]. With such computational speedup, it becomes feasible to discover non-standard screws, including oblique triangular arrangements, suited for particular high-angle fracture lines. Table 3 below provides a more detailed look at how AI models are applied to structural and biomechanical optimizations.

Table 3 *Application of the AI in optimizing orthopaedic structure fixation*

Study	AI method	Optimization target	Mechanical Core / Clinical Application	Key Outcome
[7]	Random Survival Forest (RSF)	Tabular Prognostic Prediction	Long-term mortality risk analysis after hip fracture surgery	Achieved C-statistic of 0.83 (30-day) and 0.75 (1-year) mortality; highlights multi-variable prognostic capabilities using clinical datasets.
[45]	Random Forest, XGBoost, Generalized Linear Models	Tabular Prognostic Prediction	Preoperative mortality risk prediction (1–12 months) after hip fracture	XGBoost model yielded best calibration (AUC ≈ 0.81); developed clinical decision-support tool
[13]	Deep Convolutional Neural Network (EfficientNet-B4)	Diagnostic Classification	CAD system for hip fracture detection on plain radiographs	96.1% accuracy; establishes baseline automated computer-vision pattern recognition.
[46]	Deep Learning with Multitask Network	Diagnostic Classification	Diagnosis and grading of osteoporotic vertebral fractures on plain radiographs	Accuracy 97.4%, sensitivity 84%, specificity 97%; robust external validation on 1,276 X-rays
[8]	Deep Learning (CNN + Vision Transformers)	Diagnostic Classification	Automatic classification of atypical vs normal femoral fracture.	Achieved an AUC 0.987 and sensitivity from 0.796 to 0.903, indicating more accurate and sensitive detection of AFF
[47]	Machine Learning: Decision Tree (DT), Multilayer Perceptron (MLP), Support Vector Machine (SVM)	FEA Computational Acceleration	Femoral shaft fracture plate-screw fixation; analyzed Ti-6Al-4V vs 316L SS materials; 1-3mm fracture gaps; 400-1200N axial loads	MLP and SVM showed better prediction accuracy than DT; Ti-6Al-4V had lower von Mises stress; FEA+ML enables efficient implant biomechanics prediction

Study	AI method	Optimization target	Mechanical Core / Clinical Application	Key Outcome
[48]	Graph Neural Network (GNN) surrogate models	FEA Computational Acceleration	Proximal femur fracture modeling with mechanical damage; surrogate replaces computationally expensive FEA	GNN surrogate enables efficient fracture prediction (specific metrics not fully available in search results)
[49]	Deep learning algorithm for automatic lytic tumor segmentation	improve pathological femoral fracture prediction by incorporating tumor segmentation into FEA	CT-based autonomous FEA (Simfini system) for orthopedic oncology; predicts pathological fracture risk from metastatic tumors	DL segmentation + FEA produced elevated averaged principal strains, better predicting pathological femoral fractures; DL matched manual segmentation in 19/23 regions

3.6 Artificial Intelligence (AI) and Robotic-Assisted Techniques Applied in Orthopedic Surgery

AI does more than just assist in diagnosis; it also helps with preoperative planning and robotic-assisted orthopedic surgery. Developments in robotic systems, along with smart vision and learning algorithms, have changed orthopedic surgery from a purely manual process to one based on data and precision. With AI integration, smart navigation systems that use 3D graphics and motion-tracking data allow real-time feedback on optimal implant position, screw angle and limb alignment, minimizing intraoperative errors, lowering fluoroscopy use and improving surgical precision [50]. AI also improves postoperative rehabilitation by using wearable rehabilitation technology and motion recognition algorithms. It also capable to allows the real-time image guidance, tactile feedback, and learning feedback loops which allows more precise implant positioning, reduces soft tissue damage, and lowers revision rates.

Nevertheless, from the perspective of structural engineering, it becomes crucial to differentiate between the concept of "surgical placement accuracy" and true "biomechanical configuration optimization". The present robotic systems like TiRobot and TianJi operate with sub-millimeter accuracy in implementing predetermined screw placement trajectories. However, the design features of their software architectures are mostly represented by the algorithms of rule-based or purely geometrical alignment cycles. They do not have any opportunities to implement active simulation of real-time mechanical stresses in the region, calculation of Von Mises strain distributions under functional loadings, or adjustment of screw placements depending on local bone mineral density. As it is shown in Table 4 below, existing applications of robotics include various anatomical sites from the pelvis to the spine and calcaneus; however, their main aims are still limited to geometrical path planning, trajectory-tracking, and fracture reduction kinematics.

Table 4 *Application of the AI and robotic-assisted techniques in geometric path planning versus the biomechanical limitations*

Study	AI framework	Anatomical Application	Mechanical Input	Primary Optimization & Clinical Execution Metrics	Engineering Limitation
[50]	TiRobot-3D navigation (rule-based + feedback algorithm)	Femoral neck fracture – percutaneous cannulated screw placement	Percutaneous screw axis parallelism	Reduced intraoperative bleeding (8.2 vs 36.4 mL), improved screw parallelism (24.0 ± 0.6 vs 21.5 ± 1.2), and 50% less fluoroscopy	Evaluates geometric trajectory alignment but lacks structural stress-field computing

Study	AI framework	Anatomical Application	Mechanical Input	Primary Optimization & Clinical Execution Metrics	Engineering Limitation
[51]	Robotic trajectory optimization with 3D path-planning algorithm	Pediatric Slipped capital femoral epiphysis (SCFE)	Entry accuracy & spatial path optimization	Improved entry accuracy (1.13 mm deviation), lower radiation dose (6.56 exposures/screw), and increased postoperative hip score (Harris 89.6 ± 7.5).	Purely geometric trajectory planning lacking real-time finite element stress-field computation, force-feedback haptic control, and adult Pauwels type III high-angle shear loading parameters.
[52]	Orthopedic robot + computer-assisted motion planning	Sarcopenic femoral neck fracture fixation	Spatial screw alignment matrix	Robot-assisted placement achieved superior screw alignment, faster operation, and reduced necrosis rate, improving early rehabilitation outcomes.	Static geometric navigation that lacks real-time stress analysis, dynamic compensation for tool-bone deflection, and functional mechanical compatibility with high-shear proximal femur loading.
[53]	AI-guided robot navigation (TianJi system)	Nondisplaced pelvic fracture stabilization	Spatial guidewire trajectory tracking	Significantly fewer fluoroscopic exposures, minimal blood loss, and higher accuracy vs. freehand; proposed as optimal minimally invasive technique.	Static path tracking failing to compensate for congenital malformations or canal stenosis, with no autonomous reduction for multi-ring rotational instability or real-time joint stress modeling.
[54]	TiRobot machine-vision navigation with accuracy classification (Gertzbein–Robbins)	Sacroiliac joint fixation – pelvic ring fractures	Multi-planar screw path validation	AI navigation improved screw accuracy to 92.6% vs. 78.6% (manual), with lower fluoroscopy dose and fewer punctures.	Purely geometric spatial verification lacking haptic force-feedback to prevent tool skidding on osteoporotic bone, with no capacity for finite-element based construct stiffness modeling under high-shear proximal femur loading.
[55]	TiRobot-assisted minimally invasive system + intraoperative learning algorithm	Calcaneal fracture fixation	Sustentaculum tali screw path optimization	Reduced blood loss (17.5 mL vs 45 mL) and postoperative complications; supported enhanced recovery (ERAS) through AI-based planning precision.	Geometric path tracking lacking autonomous fracture reduction, real-time tool depth sensing, and structural multi-screw stiffness optimization under high-shear proximal femur loading.

Study	AI framework	Anatomical Application	Mechanical Input	Primary Optimization & Clinical Execution Metrics	Engineering Limitation
[56]	Robot-assisted trajectory tracking with image fusion and CT-based guidewire–screw consistency analysis	Spinal internal fixation (thoracic/lumbar) using TiRobot	Guidewire-to-screw positional consistency	Confirmed that cannulated screws maintain 85% positional consistency over solid variants; quantified deviation margins.	Static geometric planning lacking haptic feedback, causing uncompensated tool deflection and trajectory deviation during the manual transition from guidewires to final screws.
[57]	AI-Intelligent Fracture Reduction Robot (3D vision + statistical shape model + elastic traction)	Femoral shaft fracture closed reduction	3D statistical shape modeling & traction path	Reduced fluoroscopy by 70%, improved femoral alignment (length difference 1.74 mm vs. 4.16 mm), and anteversion error (3.66° vs. 13.81°).	Optimizes gross anatomical bone alignment (macro-level kinematics) but ignores internal fixator mechanics.

4. Discussion

4.1 Comparative Biomechanical Performance of Cannulated Screw Configurations

Cannulated screw configuration influences the fixation stability of Pauwels type III femoral neck fractures, particularly for configurations on the shear resistance, rotational stability, and risk of nonunion of the fracture [57][60]. Of the configurations studied, the inverted triangle configuration obtained higher union rates, lower probabilities of nonunion, and optimal stress distribution relative to the upright configuration in both the clinical and computational studies. The clinical reliability of the inverted triangle configuration lies in its relative mechanical reliability as the clinical fixation of fractures hinges on maintaining mechanical stability on the fracture fixation. Ward's triangle and suboptimal trabecular bone configuration results in uneven concentration of mechanical stress on the weaker trabecular bone, as underscored in the research of Trikha et al. [23] and Li et al. [7]. For this reason, upright triangles demonstrate inferior shear and torsion resistance when compared to the inverted configuration. Chantarapanich et al. [26] proposed that the upright triangle configuration could reduce the counteractive screw strain on the neck in smaller Asians; however, this analysis was only based on a Pauwels II model which further limits its applicability to Pauwels III fractures, and this is particularly relevant in older patients. In this case, the inadequate bone quality is a reason to use three parallel screws which may be a practical and less invasive technique in older patients that provides adequate fixation strength.

Moreover, numerous finite element, cadaveric, and clinical examinations have demonstrated that the oblique triangular arrangement has superior biomechanical performance to the inverted and upright triangular configurations. Biomechanically, the oblique triangle geometry has greater shear and fatigue resistance as compared to inverted triangles, which is correlated with the lowered peak von Mises stress, reduced displacement, and femoral-head micromotion under static and cyclic loads [27][32][34]. The oblique configuration likely exploits the elliptical geometry of the isthmus of the femoral neck more effectively, as the screws have been positioned further apart in the greater inscribed area, the perimeter, and the oblique position, increasing inter-screw distance and moving the screws more distally away from the axial center. This configuration reduces stress concentration and increases the uniformity of axial load distribution across the femoral neck [19][31]. Still, some computational analyses remain to be validated clinically and in vitro, as the biomechanical and healing complex predictors under practical conditions need to be confirmed.

4.2 Influence of Adjunct Fixation Strategies

Implant augmentation, either through a medial buttress plate, additional screw insertion, or use of cross/off-axis fully threaded screws, results in a considerable increase in the stiffness of the construct and reduction of implant failure rates in high shear Pauwels III fractures [3][19][37]. Studies assessing the mechanical performance of 7.3 mm cannulated screws on Asian morphometric femora suggested that the performance of this screw diameter and morphometric wedge was superior and provided enhanced screw purchase and resistance to bending compared to smaller screws [30][31][32].

However, the majority past studies in Asian population rely on Chinese CT models or datasets that are limited in scope and do not adequately capture the morphometric diversity of Japan, Korea, Thailand, India, and Malaysia [24][58]. Morphometric diversity affecting screw spacing and convergence include neck-isthmus width, head diameter, and neck-shaft angle. Consequently, future studies ought to use multicentre CT datasets and conduct size-sensitivity analyses validated by cadaveric and experimental studies. In the great majority of cases, especially in the absence of advanced surgical resources, the inverted triangle should be the most common configuration used clinically, and the oblique triangle should be prioritized whenever possible. For vertically oriented Pauwels III or unstable fractures, additional aids such as buttress plating or cross-axis screws should be used, and these remaining recommendations should be as patient-centred as possible.

4.3 AI and Robotic-Assisted Fixation: Precision, Navigation, and Biomechanical Validation

The usage of AI and robotics within orthopedics could increase the level of accuracy pertaining to screw placement and trajectory planning, and biomechanical validation. Systems like TiRobot, TianJi, and other guided 3D navigation systems provided remarkable improvements of accuracy to over 92% screw placement accuracy and remarkable improvements within the reduction of fluoroscopy time and therefore radiation exposure [53] [54] [54]. Zhu et al. [53] and Dai et al. [55] demonstrated that robot-assisted trajectories align closely with preoperative FEA-optimized vectors, thereby enhancing reproducibility and reducing localized stress concentrations in the soft tissues surrounding the fracture line.

Screws insertion now allows for real-time updates and adaptive changes even while navigation is AI driven. For Zhao et al. [57] AI boosted navigation improved screws placement consistency to 85% vs. 69.8% for freehand. The study designed a smart fracture reduction robot that integrated 3D vision with statistical shape modelling to reduce fluoroscopy use by 70% and achieve alignment deviations of sub 2mm. These findings indicate the use of AI in robotics for intraoperative analytics and postoperative stability. Yin et al. [52] demonstrated that robot-assisted cannulated screw fixation significantly improves the safety and precision of healing outcomes for complex femoral neck fractures. AI integrated with robotic systems moves from navigation systems to intelligent execution of complex biomechanical tasks. Closing the loop with stress visualization and robotic feedback is a goal in automation for robotics. Fracture fixation will be optimized when robotic systems merge the anatomy of a patient with the mechanical aims of the fixation and the surgical methods applied.

4.4 Deep Learning and Machine Learning in Orthopedic Diagnostics and Surgical Planning

The integration of deep learning (DL) techniques with machine learning (ML) approaches has begun to reshape orthopedic diagnostics, preoperative planning, and computational biomechanics. DL techniques and, in particular, Convolutional Neural Networks (CNNs) like U-Net and EfficientNet, permit the automation of bone structure segmentation, fracture line identification, and 3D reconstructions of patient-specific femurs from CT and MRI data [8] [13][43][45]. Besides reducing the time saved on manual preprocessing, this automation also provides the consistency needed to generate finite element analysis (FEA) models, which are the foundational models for digital twin simulations and predictive simulations for fracture mechanics and the healing fractured outcomes. As an illustration, Chung et al. [43] used a deep CNN for proximal humerus fracture diagnostics and achieved an AUC of 1.00, demonstrating better performance than surgeons. The AUC (Area Under the ROC Curve), which shows a model's ability to correctly identify positive and negative cases where the value close to 1.0 is denotes perfect accuracy. Sato et al. [13] developed a CNN-based CAD system for hip fracture classification which achieved an accuracy of 96.1% from a dataset of over 5,000 X-ray images. Schilcher et al. [8] classified atypical femoral fractures using radiographs combined with electronic health records and achieved an AUC of 0.987. Further extending this line of work, Shen et al. [46] excelled in vertebral segmentation and fracture grading, exceeding 97.4% accuracy, while incorporating real-time spinal digital twins.

Machine learning (ML)enhances these systems by converting diagnostic imaging into predictive biomechanical analytics. Several algorithms, including Random Survival Forests (RSF), Random Forests, and XGBoost, have been applied successfully, with C-statistics values exceeding 0.8, to assess the probability of postoperative mortality, implant failure, and healing after hip fractures [45]. As far as computation is concerned, ML is applied within the defined context as a surrogate modelling tool for FEA. It derives the relationships of stress distribution, screw arrangement, and failure probability from previous simulations, thus learning to predict a model. By integrating model accuracy with significant reductions in computational cost, it accomplishes quick evaluations of fixation scenario samples.

In this regard, the integration of DL and ML technologies represents a significant change in orthopaedics. It shifts research from image-based, diagnostic-focused tools toward the predictive dimension of data-powered simulations. It enables the construction of digital twin's virtual representations of a patient's anatomy, fracture mechanics, and various configurations of cannulated screws that forecast performance simulations under varying dynamic loads. Such integration of imaging, ML, and FEA constitutes a decisive move toward personalized orthopaedics and, more importantly, a means to reduce the biomechanical uncertainty inherent to a diagnosis. It actively works to close the diagnostic and functional surgical biomechanics gap.

4.5 Integrating Artificial Intelligence with Configuration and Dimensional Optimization of Cannulated Screws

The incorporation of artificial intelligence (AI) into orthogonal surgery has specific relevance to the unsophisticated application regarding the optimization of cannulated screw configuration and dimensional parameters pertaining to Pauwels type III femoral neck fractures. The majority of the literature involves the refinement of surgical navigation precision and the aid of robots, concentrating on the range of intraoperative performance, as opposed to the dynamic optimization of screw geometry, spacing, and orientation for the individual femur. There is a notable absence of research involving the AI and the cannulated screw configuration as well as the dimensional optimization, which highlights a major research void in orthopedic biomechanics and the surgical technology domain where Duan et al.,[50] utilized the AI approach which is TiRobot for fixation the cannulated screw in femur bone but did not study about the morphometry of the femur to determining the optimal screw spacing, diameter and configuration. Similarly, Dai et al. [55], Yin et al. [52], and Zhu et al. [53] improved robotic systems to achieve better screw alignment and surgical precision in the pediatric and adolescent populations, respectively. However, the systems still used preset trajectories which did not allow for real-time, adaptive biomechanical control, nor AI-assisted design optimization. Zhou et al. [57] also demonstrated the advantages of robotic fixation in sarcopenic patients by improved alignment, decreased operative time, and most importantly, the lack of AI-based control to modify screw design for better angular configuration to achieve improved load sharing in the osteoporotic bone. Overall, robotic surgery is certainly more accurate than it once was, but to use AI in design, screw placement, and biomechanical analysis is still very under researched.

Moving forward, implanted AI analytics should be integrated with basic biomechanical concepts pertaining to screw configuration, screw placement, and control of forces at the femoral neck. Future efforts should comprise:

- Deep-learning segmentation frameworks to extract and characterize cortical and cancellous bone and geometry of the femoral neck;
- Classification and Regression analytical frameworks of machine learning to devise screw parameter (diameter, pitch, angle) relationships to stress dissipation, micromotion, and fatigue which affects union; and
- Reinforcement-testing of control loops for screw geometry and positioning to determine and minimize stress concentration and maximize durability under simulated physiological loads.

Integrating AI data processing with finite element modelling (FEM) will enable future orthopaedic systems to determine real-time, patient-specific configurations, and dimensions of screws and optimize the mechanical stability with biological preservation and healing potential. The combination of deep learning, machine learning and reinforcement learning in robotic-assisted systems will be the new orthopaedic transformative innovation, making the fixation transition from navigation-based to autonomous design optimization of screws. This forms the foundation for tailored and automated analytics in orthopaedic surgery, particularly for complex cases like Pauwels type III femoral neck fractures, in which postoperative results are largely determined by the shear stability of the screws and the geometric configuration of screws and their constructs.

5. Conclusion

In the case of Pauwels type III femoral neck fractures, the configuration of the screws is critical for determining the stability of fixation, along with the innovative influence of artificial intelligence (AI) in the field of biomechanics. The oblique triangular configuration is the most biomechanically favorable, naturally orienting with the elliptical neck isthmus to enhance load sharing and reduce peak von Mises stress and adolescent micromotion. The inverted triangular configuration, however, also reliably engages the calcar and remains clinically acceptable, whereas the upright triangle is problematic as it tends to traverse the weaker trabecular zones, stress concentration, and stability aggravation. For highly vertical or unstable Pauwels type III fractures, specific reinforcement, like medial buttress plating, fully threaded or off-axis screws, and the like, is targeting anti-shear resistance and contributes to enhancement of rotational stability. However, the added surgical time, cost, and need for specifically designed fixation devices/implants are the main drawbacks to the use of these techniques in rural or economically disadvantaged environments. In contrast, the cost on the surgical side remains the same when switching from an inverted to an oblique triangular configuration with the same three 6.5–7.3 mm cannulated screws, just changing their insertion angles under fluoroscopic guidance where improves shear and fatigue resistance.

Research focusing on the integration of AI with cannulated screw configuration and dimensional optimization is limited. Although current robotic systems reach placement accuracy within sub-millimetres ranges, they still do not modify the screw geometry, spacing, and load distribution adaptively and optimally. Looking ahead, deep learning and machine learning, along with finite element modelling (FEM), would create a paradigm shift in the field by allowing a data-driven approach to optimally adjust screws for the patient. Automated deep learning would reorganize the segmentation process of a patient's femur, and under reinforcement learning, the orientation of the screw could be dynamically altered within the simulated load to reduce stress concentration, thereby enhancing the lifetime of the implant.

As conclude, the oblique triangular three-screw configuration is the most effective in balancing biomechanical efficiency with practical clinical applicability, especially in the lower-resource surgical contexts. The next major step in the field is the integration of biomechanical modelling paired with real-time AI to shift the paradigm on orthopaedic fixation towards personalization. Screw placement and modification will be no longer empirically determined; rather, these parameters will be computationally generated to the patient's unique bone structure and fracture dynamics.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

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