Iraqi JMS

Published by Al-Nahrain College of Medicine
P-ISSN 1681-6579
E-ISSN 2224-4719
Email: iraqijms@colmed.nahrainuniv.edu.iq
http://www.colmed-alnahrain.edu.iq
http://www.iraqijms.net\
Iraqi JMS 2025; Vol. 23(1)

Imaging and Simulation Techniques for Lower Limb Deformity: A Literature Review

Batool A. Akar[1] *BSc*, **Aseel M. Ghazwan**[1] *PhD*, **Waleed A. Al-Saadan**[2] *FICMS*

[1]Dept. of Biomedical Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq, [2]Medical City Teaching Complex, Baghdad, Iraq

Abstract

Malalignment syndrome involves improper anatomical positioning due to musculoskeletal abnormalities, often resulting in torsional deformities that impair function and require surgical intervention. Traditional surgical planning methods have limitations in precision and consistency. This review aimed to explore recent advances in computer-aided surgical simulation and digital 3D skeletal modeling techniques used to assess and correct lower limb deformities. It was conducted to analyze current methods in 3D surgical planning, focusing on computer-aided simulations and the use of personalized surgical guides. Sources were selected from peer-reviewed journals and databases, evaluating their applications in clinical practice. Studies showed that computer-assisted surgical simulation enhances preoperative planning, improves alignment accuracy, reduces intraoperative complexity, and decreases surgery time. Personalized guides developed from digital modeling have demonstrated improved outcomes and reduced surgical trauma. Computer-aided 3D modeling and personalized surgical planning represent significant advancements in deformity correction. These tools provide surgeons with improved visualization, simulation capabilities, and efficiency, ultimately supporting safer and more accurate surgical interventions.

Keywords Computer-aided surgical simulation, surgical planning, 3D motion analysis

Citation Akar BA, Ghazwan AG, Al-Saadan WA. Imaging and simulation techniques for lower limb deformity: A literature review. Iraqi JMS. 2025; 23(1): 1-16. doi: 10.22578/IJMS.23.1.1

List of abbreviations: 3D = Three-Dimensional, AP = Anteroposterior, CAD = Computer-aided design, CT = Computed tomography, DDH = Developmental dysplasia of the hip, EMG = Electromyography, fMRI = Functional magnetic resonance imaging, LLD = Leg length discrepancy, LAT = Lateral, MRI = Magnetic resonance imaging, PRISMA = Preferred reporting items for systematic reviews and meta-analyses, RSA = Radio stereometric analysis, X-ray = Radiograph (X-radiation)

Introduction

Torsional deformities are bone abnormalities causing skeletal malalignment from improper turning or twisting of the long bones along their axes. The malalignment may be broadly classified into anteversion, retroversion, and torsional discrepancy [1,2]. Anteversion is a condition in which loading is not directly vertical through the hip and knee joint line; hence, normal weight transmission is impaired. Retroversion symptoms are relatively mild and may frequently remain undetected. Torsional discrepancy is a clinical diagnosis reflecting bothersome effects of anatomic malrotation [3, 4]. These deformities can cause joint discomfort, gait patterns alteration, early osteoarthritis, and functional restrictions if left untreated [5-7]. As a result, early diagnosis and precise assessment are critical to guide treatment decisions and avoid the development of these disorders [8].

A full physical examination typically serves as the first step in the clinical assessment of lower limb deformities. Subjects of all ages may be assessed using different imaging tools for a precise diagnosis. Even radiographs and computed tomography (CT) are limited in measuring the rotational malalignment of one bony segment in their static positions, and measurements of the bony torsion may not actually reflect aspects regarding the soft tissues [9,10]. Measurements of intercondylar distance for genu varum and intermalleolar distance for genu valgum are typical in clinical practice [11]. These measures provide a rough estimate of the severity of deformity [12,13]. Nevertheless, they are frequently affected by a group of factors such as patient size and are not usually precise enough to guide surgical procedures [14].

Accurate identification of rotational abnormalities, including femoral anteversion and tibial torsion, depends on the sophisticated imaging technologies since clinical assessments by themselves does not offer the sufficient evaluation [15-17]. Furthermore, in cases of congenital defects or related developmental abnormalities, leg length discrepancy (LLD) requires exact measurement to determine whether the discrepancy results from the femur, tibia, or both structures [18-21].

Correctly evaluating lower limb abnormalities depends critically on radiological imaging [5,22], especially in cases involving angular abnormalities such genu varum or genu valgum, full-length, weight-bearing X-rays remain the preferable technique for evaluating the alignment of the lower extremities [23,24]. When examining deformities, CT scans have clear benefits; they also give a comprehensive three-dimensional (3D) image of the lower limb, which is absolutely vital [11,25-27]. Preoperative planning depends on these imaging modalities especially when exact measurements are needed to specify the degree of correction needed [28,29].

Lower limb abnormalities' examination and diagnosis have been much improved by developments in medical imaging technology including 3D modeling and biplanar radiography. While both conventional X-rays and biplanar radiography provide anteroposterior (AP) and lateral (LAT) views, they are not the same in terms of technology or diagnostic utility. By capturing simultaneously frontal and lateral images, biplanar radiography generates 3D models of the lower limbs, therefore enabling more accurate assessments of limb length and alignment under weight-bearing situations [19,30,31]. Particularly in complicated multi-planar abnormalities, this technique is extremely helpful when conventional X-rays might not offer sufficient detail [32]. Furthermore, 3D modeling aids in personalized surgical planning, allowing surgeons to simulate corrective interventions and anticipate outcomes prior to surgical procedures [33].

Motion capture systems and gait analysis technologies have also emerged as important tools for evaluating the functional consequences of lower limb deformities [34,35]. Through real-time measurement of joint movements, these technologies provide dynamic information regarding the effects of deformities on the gait cycle, yielding critical insights essential for surgical planning as well as postoperative rehabilitation [36,37]. Protocols for assessing lower limb deformities must be standardized so that doctors throughout the world can receive consistent, reliable findings. Another problem is the availability of modern imaging technologies like CT, magnetic resonance imaging (MRI), and biplanar radiography. These technologies, while very precise, are costly and may not be easily available in resource-constrained contexts. Furthermore, the interpretation of imaging data can be challenging, particularly when both femoral and tibial deformities are present, or there is substantial bending or rotation of the bones [38,39].

Genu varum and genu valgum, two of the most common lower limb deformities, are normally diagnosed using radiological and clinical approaches. Genu varum (outward bending of the legs) and genu valgum (inward angling of the knees) can cause aberrant joint loading and increased stress on the medial or lateral compartments of the knee [40]. These deformities are predominantly identified in childhood, and prompt intervention is essential to prevent long-term repercussions, which may encompass osteoarthritis and other limb deformities. Surgical intervention, such as osteotomy, is often used when the deformity degree is severe or results in significant functional impairment in the limbs [41-43]. Radiological data, namely the tibiofemoral angle and mechanical axis, are essential for planning these surgeries and ensuring the right degree of correction is achieved [44,45].

The main objective of this review is to objectively examine and compare various approaches for diagnosing limb deformities, including torsional deformities. It seeks to investigate the evolution, benefits, and limits of both traditional and innovative methodologies.

Methods

Questions of research

Specific study questions were developed to conduct a thorough assessment of computer-aided surgical simulations used to treat deformities. The questions aimed to assess the usefulness, difficulties, and possibilities of digital 3D skeletal modeling in clinical practice. The main research questions are:

Q1. What are the optimized parameters for mimicking the 3d skeletal segments model in individuals with malalignment?

Q2. What are the advantages of computer-aided surgical simulation over traditional approaches for correcting deformities?

Q3. What are the obstacles of using digital dynamic 3D skeletal segments in clinical practice, especially for surgical planning of deformities?

Q4. What innovations in technology are able to improve the precision and accessibility of computer-aided simulation for deformity correction?

Selection criteria

A comprehensive assessment of the relevant literature was carried out in accordance with the standards provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines shown in figure (1). Databases such as PubMed, Springer, Scopus, and Web of Science were utilized in order to get the research papers that were employed is shown in figure (2) and the year wise publication is shown in figure (3). The procedure of filtering consisted of identifying keywords, then screening titles and abstracts, and finally doing a comprehensive evaluation of full-text publications by reading them in their entirety.

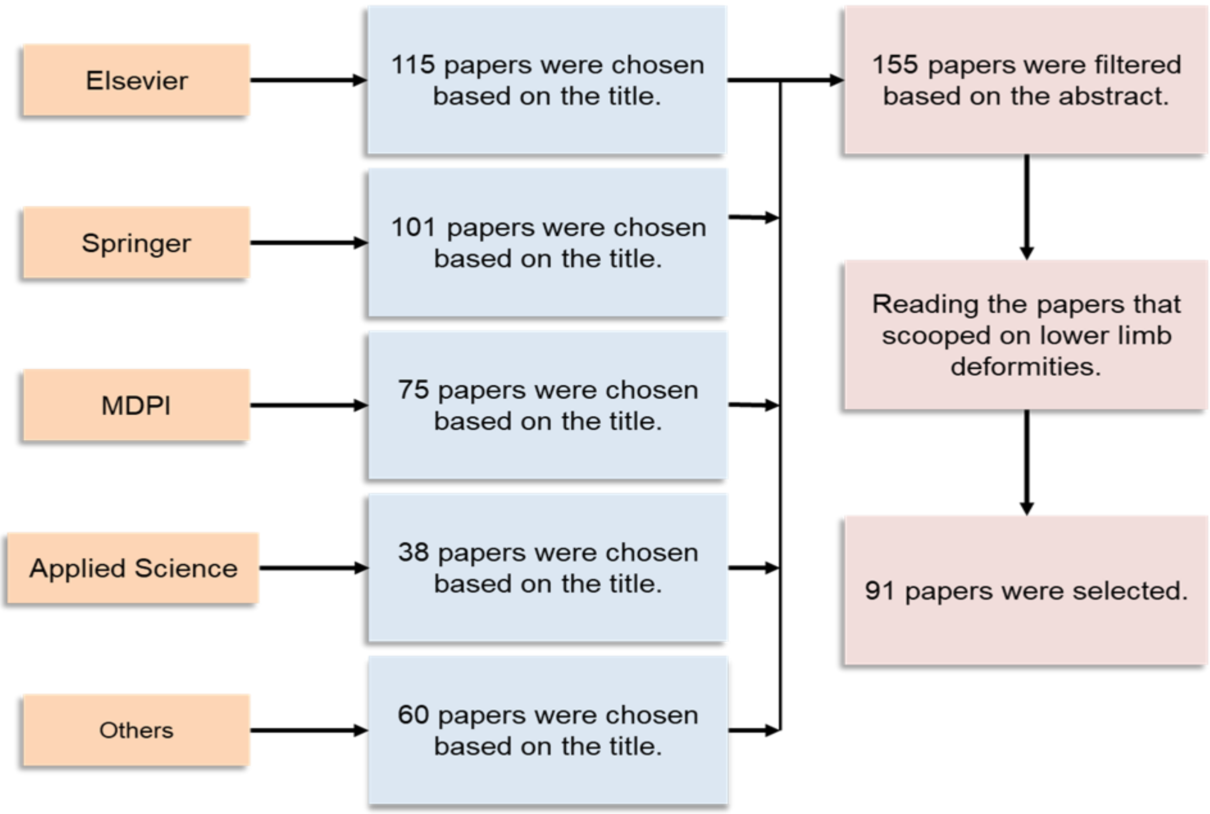

Figure 1. PRISMA layout representation for the paper selection strategy

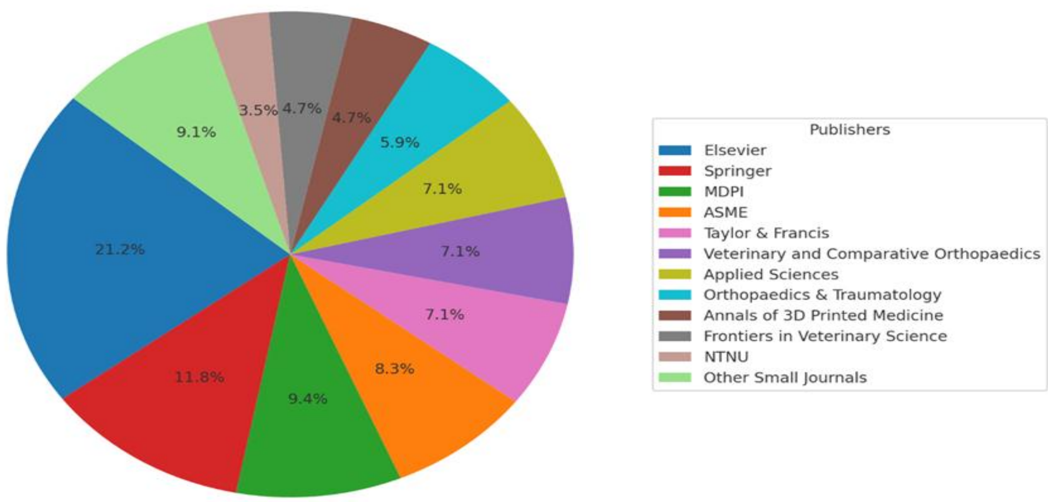

Figure 2. Publisher selection distribution

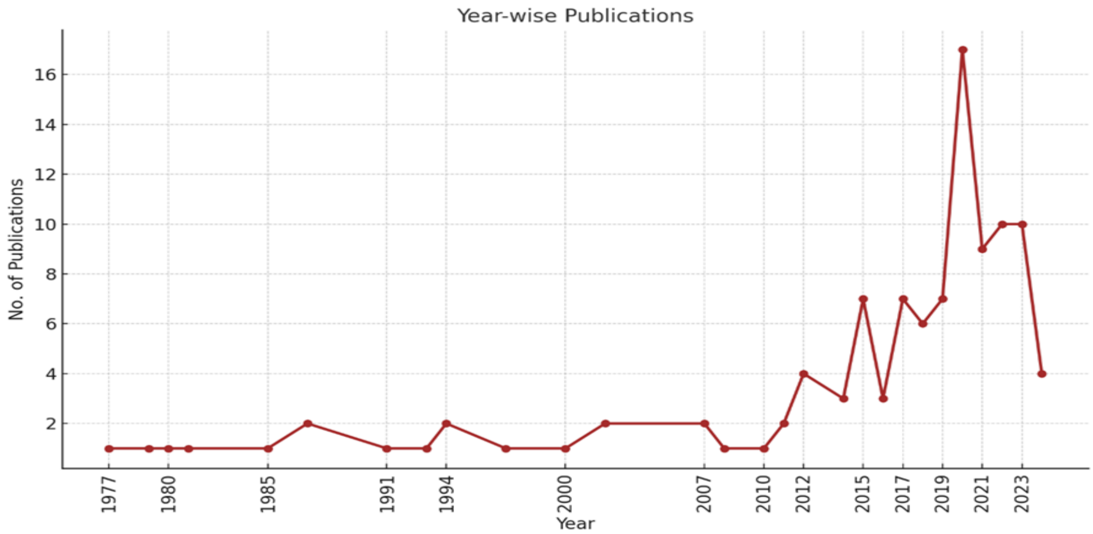

Figure 3. Year-wise distribution of the selected papers

The motivation for the study

The impetus for this review was the increasing necessity to address deformities in individuals with lower limb malalignment. These deformities can have a profound impact on mobility, resulting in long-term joint degeneration and gait deformities. The emergence of computer-aided simulations has enabled a more dynamic and personalized approach, as traditional methods have been centered on physical assessments or static imaging. This review aimed to address the research void and offer a more comprehensive understanding of the role of sophisticated simulations in surgical planning and correction by evaluating the efficacy of digital 3D skeletal modeling.

Inclusions and exclusions

The criteria for inclusion and exclusion in this review are presented in table (1).

Table 1. Reference classification

Inclusions	Exclusions
Studies involving patients diagnosed with deformities or malalignment in the lower limbs	Studies involving patients without such deformities or focusing on conditions unrelated to the lower limbs
Research that utilizes computer-aided surgical simulation techniques or digital 3D skeletal models for planning or executing surgical corrections	Research that does not use computer aided surgical simulation
Studies reported outcomes related to the effectiveness of surgical interventions, including changes in alignment, functional outcomes, or patient-reported outcomes.	Studies lack clear data on outcomes related to surgical effectiveness or methodological details necessary for evaluation
Peer-reviewed articles, clinical trials, or observational studies that provided sufficient data on the methods and outcomes	Exclusion of literature reviews, meta-analyses, or editorials without original data
Research conducted across multiple centers or institutions that provides a broader perspective	Studies with a sample size that is too small to draw meaningful conclusions

Approaches to the analysis

Particularly in patients with malalignment, researchers have evolved several techniques over years for evaluating deformities in the lower limb [41]. There are numerous periods of development to which these methods fit, each with benefits and drawbacks. Manual goniometry, which directly evaluated joint angles [46] and other anthropometric measurements like leg length disparities and knee rotation evaluations [47-49] were among the conventional techniques. But these techniques may lack accuracy and may be swayed by examiner prejudice [35]. More complex imaging technologies including computer-aided design (CAD) systems and 3D motion analysis have lately been brought by recent developments [50]. These techniques provide thorough kinematic data that can be statistically examined, hence improving the evaluation of lower limb mechanics [6,51,52]. For example, 3D motion capture systems have been demonstrated to increase the accuracy of deformity assessments and enable the exact tracking of joint motions [52,53]. Likewise, CAD technologies help to simulate surgical operations, therefore enabling a more customized approach to fix deformities [1,54].

Apart from these methods, CT scans and MRI showed high-resolution images of skeletal structures [4,25]. Though these techniques are more precise than the conventional ones, they expose patients to ionizing radiation and are usually costly [55]. Moreover, depending on the examiner's abilities, hand measurements of angles obtained from these images might bring variety [17].

One exciting path forward is the combination of cutting-edge technology including computer modeling and ultrasonic waves. While computer modeling offers a reasonably affordable way to observe and simulate deformities without the consequences of radiation exposure, ultrasound offers a non-invasive alternative that can record real-time soft tissue dynamics [56-58]. The demand for dependable, quick, non-invasive evaluation tools that can efficiently handle the complexity of deformities drives these developments mostly [58-60].

Future studies should concentrate on standardizing these techniques to improve their dependability and accuracy as well as looking at their sensitivity to variances in patient demographics and deformity types [61]. The aforementioned approaches are summarized in Table 2.

Table 2. Approach analysis

Approach of Analysis	Advantage	Disadvantage	Limitation
Visual and clinical assessment	Rapid, non-invasive, and does not require equipment helps guide, further assessments and imaging decisions	Subjective, heavily dependent on clinician's experience, may miss subtle deformities	Variability between clinicians can lead to discrepancies, may require further objective tests for accuracy
Goniometry	Provides precise joint angle measurements non-invasive, simple to use, and widely accessible	Measurements can be inconsistent depending on technique, patient positioning, and equipment	Standardization across users is necessary for consistent results, manual interpretation introduces variability
Radiographic techniques (X-ray)	Provides clear images of bony structures, immediate results, and allows for angle measurements (eg, Cobb)	Exposure to ionizing radiation, concerns in pediatric populations	Manual interpretation introduces variability, limited soft tissue detail
Computed tomography (CT)	High-resolution, cross-sectional, 3D reconstructions for detailed anatomical assessments	Higher radiation exposure than X-rays, costly	Limited availability in some settings, and high radiation dose, especially concerning for younger patients
Magnetic resonance imaging (MRI)	Excellent for soft tissue imaging, non-invasive, and free of radiation, ideal for complex deformities	High cost, longer scan times, and requires specialized training for interpretation	Limited availability in some areas, and difficulty capturing detailed bony structures
3D Motion capture systems	Provides objective, dynamic analysis of joint movement and gait deformities with high precision	High equipment cost and the need for specialized training, time-consuming assessments	Limited accessibility in clinical settings, complex data processing needed for full analysis
Ultrasound Techniques	Non-invasive, real-time imaging of soft tissues, dynamic assessments, and widely accessible	Operator-dependent, limited detail on bony structures	Highly reliant on clinician's skill, provides less detailed information on bones compared to radiographic techniques
Photogrammetry	Non-invasive, cost-effective, generates detailed 3D models, and tracks deformities over time	Lighting conditions and camera quality can affect accuracy Limited to surface anatomy evaluations	May not capture detailed internal structures like bones, variable results based on imaging conditions
Computer-aided surgical simulation	Provides detailed 3D models using CT scans that allow for preoperative planning and visualization of surgical interventions, enables precise planning of corrections for complex deformities	Requires specialized software and equipment, and demands training for proper interpretation	Limited availability in some clinical settings, accuracy is dependent on the quality of input data and software used

Methods used to assess lower limb deformities

There are several ways to assess the deformity of the lower limb, these methods are listed below.

Visual and clinical assessment

Orthopedic assessment traditionally relies on visual observation and clinical evaluation to detect limb deformities, posture issues, and joint abnormalities. This involves patient history, physical exams, gait analysis, and palpation to assess function and structure. However, these methods are subjective and may vary between clinicians, potentially leading to misdiagnosis (20).

While visual assessments can detect obvious deformities, they may miss subtle issues. Incorporating objective measurement tools, such as clinical grading scales and radiographic classifications, improves diagnostic accuracy and reliability (62).

Visual assessments, when combined with imaging techniques like X-rays or MRI, offer a more complete understanding of limb deformities. Despite their limitations, clinical evaluations remain essential in guiding further diagnostic steps and treatment decisions (20).

Goniometry

Goniometry is a widely used clinical method to measure joint angles and range of motion. It involves a goniometer with fixed and movable arms aligned to body segments. This technique helps detect joint stiffness and anatomical issues, and digital versions improve accuracy and data management (63).

Goniometry provides precise joint angle measurements, aiding in diagnosing and monitoring conditions like hip dysplasia. It also helps track deformity progression and assess treatment and rehabilitation outcomes. However, its accuracy can be affected by patient posture, clinician technique, and device quality, and manual readings may vary between observers (64,65).

Radiographical Methods

Conventional X-ray imaging has long been essential for assessing limb deformities, offering clear views of bone alignment, joint spacing, and abnormalities. Until the early 20th century, it was the primary diagnostic tool in orthopedics. Its key benefit is providing immediate results, enabling quick diagnoses. Digital radiography has since enhanced image quality and diagnostic precision through advanced processing techniques (66). Software helps doctors accurately assess limb length differences and angles like the Cobb angle for scoliosis. However, X-ray imaging has limitations, including radiation risks—especially for young patients—and potential variability in interpretation due to differences in radiologist expertise (44).

Advances in imaging, such as CT and MRI, have addressed limitations of traditional methods. CT provides detailed cross-sectional views, while MRI non-invasively assesses soft tissues like muscles and ligaments. Combining these with clinical evaluations—like visual inspection and goniometry—offers a comprehensive understanding of limb deformities, improving treatment outcomes (18).

CT scan

CT scans, introduced in the late 20th century, provide detailed cross-sectional and 3D images of bones, making them essential for evaluating limb deformities. They are especially useful in complex cases like femoral and tibial torsion, where accurate assessment of bone alignment is crucial for treatment planning (62). CT scans, introduced in the late 20th century, provide detailed cross-sectional and 3D images of bones, making them essential for evaluating limb deformities. They are especially useful in complex cases like femoral and tibial torsion, where accurate assessment of bone alignment is crucial for treatment planning (65). While CT imaging can be expensive and less accessible in some cases, its use in orthopedics is growing. It is valuable for diagnosing congenital abnormalities, serious injuries, and post-operative conditions. When combined with tools like goniometry and clinical evaluations, CT offers a more comprehensive understanding of limb deformities and treatment options. As technology advances, CT imaging is expected to play a larger role in diagnosing limb abnormalities. Enhanced CT methods maintain diagnostic accuracy while lowering radiation risks, making CT highly valuable for diagnosing and treating complex limb conditions [62].

MRI

MRI is not typically used to assess alignment deformities, as it does not provide precise bony landmarks for such measurements. However, it plays a valuable role in evaluating soft tissues and joint structures in some complex deformity cases. MRI is especially helpful in cases where soft tissue pathology may influence surgical decision-making, such as ligamentous injuries, muscle atrophy, or cartilage degeneration [32]. MRI's high contrast resolution is a key advantage, allowing clear distinction of soft tissue structures. This makes it essential for evaluating complex conditions involving both soft tissue and bone, such as post-traumatic deformities [67]. MRI enhances understanding of limb abnormalities by providing functional insights, such as assessing ligament and tendon integrity or muscle activity. However, its main limitations are longer scan times and higher costs, which may limit accessibility in some clinical settings [32]. MRI interpretation requires specialized training, and its subjective nature can lead to diagnostic differences among radiologists. Despite this, MRI has significantly advanced orthopedic understanding, especially in preoperative planning, by helping surgeons visualize anatomical relationships and anticipate complications more accurately. Ongoing research explores MRI's role in monitoring treatment outcomes, especially in children where growth affects deformities. With advancing technology, MRI is expected to reveal new applications. Techniques like diffusion tensor imaging and functional MRI (fMRI) may deepen our understanding of bone-soft tissue relationships. Overall, MRI enhances diagnostic accuracy and guides effective treatment planning for limb deformities [45].

3D Motion Capture Systems

3D motion capture is an emerging tool for analyzing limb deformities during movement. It uses cameras and reflective markers to precisely track motion. Though developed in the mid-20th century, improvements in digital imaging and algorithms have made it more widely used in clinical and research settings [65]. A major advantage of 3D motion capture is its ability to deliver objective, measurable data on joint movements during activities. This is particularly valuable for evaluating gait issues caused by torsional deformities, offering a comprehensive view of their impact on function [34]. Analyzing gait patterns with 3D motion capture reveals differences in weight distribution, stride length, and joint angles, enhancing understanding of mobility issues. It also enables the creation of detailed biomechanical models, allowing doctors to simulate treatment options and predict outcomes. Preoperative simulations, for example, help plan surgeries by showing how adjustments will affect limb alignment and function [68]. 3D motion capture is valuable for designing rehabilitation plans and tracking patient progress. Despite its advantages, it faces challenges like high costs, the need for specialized training, and time-consuming procedures. Still, it has significantly advanced limb deformity evaluation, with recent studies supporting its use in assessing surgical and orthotic outcomes. With continued technological development, its role in diagnosing limb disorders is expected to grow [69].

Ultrasonic Methods

Ultrasound is a valuable tool for real-time imaging of soft tissue structures such as muscles, tendons, and ligaments. However, it is not used for evaluating bone alignment or rotational deformities. Its primary orthopedic applications include dynamic assessment of soft tissue injuries and infant hip screening (e.g., developmental dysplasia of the hip; DDH). Muscle function is best assessed clinically and with electromyography (EMG), rather than with ultrasound imaging [44]. Ultrasound provides real-time assessments of limb function during movement, allowing doctors to observe muscle contractions and analyze activity and coordination. This helps identify how muscle imbalances or weaknesses contribute to limb deformities, especially in conditions like cerebral palsy or other neuromuscular disorders [69]. Ultrasound is especially valuable for assessing limb deformities due to its real-time imaging of muscle activity and coordination, aiding in conditions like cerebral palsy. It enhances treatment by guiding procedures precisely and is a safe, non-invasive option—particularly beneficial for children. Ultrasound is affordable, accessible, and effective for diagnosing soft tissue issues and certain deformities like knee instability and hip dysplasia. However, its effectiveness relies heavily on the operator's skill, and it provides limited detail on bone structures compared to CT or X-rays. Despite these limitations, ultrasound is increasingly important in orthopedic evaluations, with ongoing research expected to expand its clinical applications [44].

Photogrammetry

Photogrammetry is a newer method for assessing limb deformities, using photographs to create accurate 3D models of anatomical structures. Advances in digital imaging and software have made it increasingly popular in clinical and research settings [69].

Originally developed in the early 19th century, photogrammetry has recently advanced in medicine, offering a non-invasive, accurate, and cost-effective tool for assessing body proportions and limb deformities. By capturing images from multiple angles and generating 3D models, it allows for precise defect measurement, tracking changes over time, and detailed surface anatomy analysis [61].

Photogrammetry is valuable for monitoring treatment outcomes in patients with congenital defects, assessing limb length differences, and evaluating posture. It also precisely tracks changes in limb geometry after surgery, helping determine treatment effectiveness [69]. Despite its benefits, photogrammetry has limitations. Its accuracy depends on factors like camera quality, lighting, and subject positioning, and it lacks the ability to visualize internal bone structures compared to X-rays or CT. However, as technology advances, photogrammetry is becoming a valuable tool in orthopedic assessments. When combined with other diagnostic methods, it offers a more comprehensive view of limb deformities and enhances treatment outcomes [70].

Computer-aided surgical simulation

Conventional imaging techniques such as X-rays provide only two-dimensional views, which may be insufficient for accurately assessing complex deformities like torsional malalignment. However, CT imaging, despite involving radiation exposure, offers high-resolution cross-sectional data that is essential for reconstructing accurate 3D models of skeletal structures. In this context, 3D surface modeling refers to the digital reconstruction of the outer geometry of bones, typically based on CT data, allowing clinicians to visualize anatomical abnormalities more clearly. This modeling enables surgeons to simulate osteotomies and other corrective procedures in a virtual environment, enhancing preoperative planning by predicting surgical outcomes and reducing intraoperative uncertainty [71]. Surface modeling has shown great benefits for surgical preparation in cases involving femoral anteversion and tibial torsion, where rotational changes may cause significant functional limits. By using surface models, doctors may more accurately assess these misalignments and create appropriate treatment plans [72].

Although surface modeling provides an accurate 3D depiction of the skeletal framework, it does not account for the effects of torsional abnormalities on mobility. To address this, motion capture technology has proven valuable. Motion capture systems use sensors to track real-time movement data, allowing for a complete understanding of how torsional deformities affect overall mobility and gait. For example, in patients with tibial torsion, motion capture can help identify compensatory movements, such as altered postures, that might not be visible through static imaging. These compensations can lead to secondary problems like joint pain and muscular strain, but motion capture allows for customized treatment plans that address both structural deformities and functional impairments [73].

Integrating motion capture data with 3D surface models enhances surgical planning by enabling the simulation of post-operative results, improving surgical accuracy, and reducing the need for revision surgeries. This combined approach also contributes to faster recovery times and better functional outcomes, allowing surgeons to tailor procedures to each patient’s unique anatomical characteristics and movement patterns [72]. The use of these advanced technologies promotes a more personalized and effective treatment approach, ultimately improving both the quality of life and mobility of patients.

Other studies

Gait analysis and radio stereometry (RSA) are advanced tools for diagnosing and treating limb issues, providing insights into joint mobility and bone stability. Gait analysis evaluates walking and running mechanics using high-speed cameras, sensors, and software, making it vital for assessing deformities and their impact on movement—especially in torsional or structural anomalies. It is essential for pre- and post-operative evaluations to gauge treatment effectiveness. However, it requires specialized equipment and expertise, and its results can be influenced by environmental and individual factors [34,69,74]. RSA uses simultaneous X-rays from multiple angles to produce highly accurate 3D models of bone movement, detecting micromotions as small as 0.1 mm. It's ideal for monitoring surgical outcomes, like in osteotomies and joint replacements. However, it is invasive due to required marker implantation and is costly [51,68,75]. Together, gait analysis and RSA offer valuable data—gait analysis for functional assessment and RSA for precise bone alignment and stability, especially in long-term studies [76].

Challenges to be addressed

These difficulties have been found by means of analyzing the deformity evaluation techniques, which have been discussed in this paper:

- CT scans and X-rays have been considered the gold standard for diagnosing deformities. However, radiation exposure and their inability to capture dynamic movement limit their usefulness making these methods not ideal for functional or ongoing assessments, underscoring the need for safer, more adaptable alternatives.
- Review of functional assessment techniques revealed tremendous potential for gait analysis and 3D motion capture in assessing deformities' functional impact. These methods, however, are very susceptible to environmental elements and call for specific tools and knowledge, which causes variations in data collecting and more expenses.
- RSA is intrusive yet accurate for measuring bone mobility; it requires surgical insertion of markers. This reduces its use in regular clinical practice and calls for the creation of less intrusive but equally exact substitutes.
- Integration of methods: there is not a single approach that can solve all the structural and functional elements of torsional

deformities. Integration of imaging and functional assessment methods can provide a more complete assessment of these defects in clinical environments.

Discussion

This study reviewed the assessment and correction of lower limb deformities, comparing traditional approaches to advances in imaging technology such as 3D motion analysis and CAD. It emphasizes the advantages of non-invasive tools for surgical planning, such as ultrasound and digital modeling, as well as the importance of standardizing assessment procedures. The questions were discussed in the questions of research section, will be addressed in the following:

Q1. What are the optimized parameters for mimicking 3D segments model in individuals with malalignment?

Surface modeling and mesh modeling are the most successful digital 3D skeletal segment modeling parameters. Surface modeling creates a complete representation of the outer form of the bone, thereby enabling flawless fitting and alignment during the simulation phase. Mesh modeling defines this shape using a network of polygons (usually triangles), allowing for precise simulation and analysis, such as stress testing or surgical planning.

Moreover, methods such as finite element analysis let one investigate mechanical behavior and stress distribution under various loads, therefore offering an understanding of how deformities could be corrected. Combining these techniques with motion capture data and computer-aided design systems increases simulation accuracy, enabling more personalized treatment plans based on the patient's anatomical and functional requirements.

Q2. What are the advantages of computer-aided surgical simulation over traditional approaches for correcting deformities?

Computer-aided surgical modeling is better than traditional methods in many ways, especially when it comes to accuracy and patient results. Traditional methods depend on steady images (like X-rays) and planning by hand, which can lead to differences and mistakes. Computer-aided modeling, on the other hand, uses high-resolution 3D models that can be moved around to look at different surgery scenarios and make better plans. Studies have shown that computer-aided models make deformity repairs more accurate by giving surgeons real-time feedback on how the surgery went. This makes it easier for the surgeon to picture and carry out complicated procedures. The results in the real world are also usually better because models can predict and prevent problems before they happen. This means that surgery takes less time, patients are better aligned, and they heal faster. Also, being able to model different surgical methods lets doctors make personalized care plans that take into account how each person's body is built.

Q3. What are the obstacles of using digital dynamic 3D skeletal segments in clinical practice, especially for surgical planning of deformities?

High technology and software expenditures as well as limited access for many clinics are the primary difficulties. Furthermore, much needed is specific training to guarantee correct application of modern technology. Large file volumes and complexity of data handling might make it difficult. Furthermore, influencing the uniformity of outcomes across many environments is a lack of defined procedures. At last, patient-specific variability complicates the prediction accuracy of these models, therefore impairing their clinical practice value.

Q4. What innovations in technology are able to improve the precision and accessibility of computer-aided simulation for deformity correction?

Computer-aided simulation emphasizes several domains to improve accessibility and accuracy. Artificial intelligence and machine learning algorithms can greatly improve modeling accuracy by means of the analysis of large datasets, identification of patient-specific outcomes generated from preoperative data, additionally giving real-time feedback throughout surgery, intraoperative CT and MRI will enable dynamic changes in the surgical plan. Provide easy-to-use interfaces for your program to let doctors with varying degrees of technical knowledge embrace it. Electronic health record integration and cost control will help to enhance communication and workflow of the healthcare team.

In conclusion, this study examined the advancements and benefits of digital 3D skeletal modeling computer-aided simulation in the treatment of torsional anomalies. These sophisticated methodologies give greater precision in surgical planning than older techniques, allowing for the creation of bespoke models and real-time alterations during surgical procedures. However, the extensive integration of these technologies in clinical environments is impeded by considerable installation expenses, the necessity for specialized training, and the lack of defined protocols. Overcoming these challenges will need initiatives to lower technological costs, improve accessibility via intuitive software, and incorporate these advancements into current healthcare systems. The potential integration of artificial intelligence and machine learning, along with advancements in real-time imaging, has the ability to enhance the precision and efficacy of remedial measures for lower limb malalignment. Addressing these limitations, new technologies promise to transform the management of abnormalities, resulting in enhanced clinical outcomes and more efficient surgical care for patients.

References

1. Staheli LT. Torsional deformity. Pediatr Clin North Am. 1977; 24(4): 799-811. doi: 10.1016/s0031-3955(16)33499-x.
2. Nejima S, Maiotti M, Schröter S. Double level de-rotational osteotomy for femoral and tibial external torsion: Report of two cases. J Orthop Rep. 2024; 3(3): 100297. doi:10.1016/j.jor.2023.100297.
3. Morasiewicz P, Filipiak J, Krysztoforski K, et al. Biomechanical aspects of lower limb torsional deformation correction with the Ilizarov external fixator. Ann Biomed Eng. 2014; 42(3): 613-8. doi: 10.1007/s10439-013-0911-6.
4. Zak L, Tiefenboeck TM, Wozasek GE. Computed tomography in limb salvage and deformity correction-3d assessment, Indications, Radiation exposure, and safety considerations. J Clin Med. 2021; 10(17): 3781. doi: 10.3390/jcm10173781.
5. Wang DC, Deeney V, Roach JW, et al. Imaging of physeal bars in children. Pediatr Radiol. 2015; 45(9): 1403-12. doi: 10.1007/s00247-015-3280-5.
6. Passmore E, Graham HK, Pandy MG, et al. Hip- and patellofemoral-joint loading during gait are increased in children with idiopathic torsional deformities. Gait Posture. 2018; 63: 228-35. doi: 10.1016/j.gaitpost.2018.05.003.
7. Strecker W, Keppler P, Gebhard F, et al. Length and torsion of the lower limb. J Bone Joint Surg Br. 1997; 79(6): 1019-23. doi: 10.1302/0301-620x.79b6.7701.
8. Morasiewicz P, Filipiak J, Krysztoforski K, et al. Clinical factors affecting lower limb torsional deformities treatment with the Ilizarov method. Orthop Traumatol Surg Res. 2014; 100(6): 631-6. doi: 10.1016/j.otsr.2014.03.019.
9. Nogueira MP, Paley D. Prophylactic and therapeutic peroneal nerve decompression for deformity correction and lengthening. Operative Techniques in Orthopaedics. 2011; 21(2): 180-3. doi: 10.1053/j.oto.2011.01.001.
10. Reif TJ, Humphrey TJ, Fragomen AT. Osteotomies about the knee: managing rotational deformities. Oper Tech Sports Med. 2022; 30(3): 150938. doi: 10.1016/j.otsm.2022.150938.
11. Otani K, Sato T, Kobayashi K, et al. Effects of three-dimensional femur and tibia postures on the parameters of standing long-leg radiographs for osteoarthritic knees in elderly female subjects. Clin Biomech (Bristol). 2024; 117: 106297. doi: 10.1016/j.clinbiomech.2024.106297.
12. Nakamura R, Kawashima F, Amemiya M, et al. Derotational hybrid closed-wedge high tibial osteotomy for knee osteoarthritis with patellar subluxation caused by tibial torsional deformity. Arthrosc Tech. 2023; 12(10): e1687-94. doi: 10.1016/j.eats.2023.05.017.
13. Giertych BF, Galli SH, Halanski MA, Lang PJ. Anterior hemi-epiphysiodesis of the distal tibia for residual equinus deformity in children with clubfeet. Journal of the Pediatric Orthopaedic Society of North America. 2022; 4(1): 397. doi: 10.55275/JPOSNA-2022-0004.
14. Jakob RP, Haertel M, Stüssi E. Tibial torsion calculated by computerised tomography and compared to other methods of measurement. J Bone Joint Surg Br. 1980; 62-B(2): 238-42. doi: 10.1302/0301-620X.62B2.7364840.
15. Thepaut M, Leboucher J, Tissot V, et al. Measurement of femoral torsion using the EOS system: Validity, reliability, and perspectives for children and adults with cerebral palsy. Annals of Physical and Rehabilitation Medicine. 2012; 55(1): e222. doi: 10.1016/j.otsr.2013.09.010.
16. Nelitz M. Femoral Derotational Osteotomies. Curr Rev Musculoskelet Med. 2018; 11(2): 272-9. doi: 10.1007/s12178-018-9483-2.

17. Link TM. Osteoporosis imaging: state of the art and advanced imaging. Radiology. 2012; 263(1): 3-17. doi: 10.1148/radiol.2633201203.
18. Paley D. Radiographic Assessment of lower limb deformities. In: Herzenberg JE (ed). Principles of Deformity Correction. Springer-Verlag Berlin Heidelberg; 2002. p. 30-60. doi: https://doi.org/10.1007/978-3-642-59373-4_3
19. Beranger JS, Dujardin D, Taburet JF, et al. Is distal femoral torsion the same in both of a patient's legs? Morphometric CT study. Orthop Traumatol Surg Res. 2018; 104(4): 481-4. doi: 10.1016/j.otsr.2018.02.014.
20. Sabharwal S, Kumar A. Methods for assessing leg length discrepancy. Clin Orthop Relat Res. 2008; 466(12): 2910-22. doi: 10.1007/s11999-008-0524-9.
21. Paley D, Bhave A, Herzenberg JE, et al. Multiplier method for predicting limb-length discrepancy. J Bone Joint Surg Am. 2000; 82(10): 1432-46. doi: 10.2106/00004623-200010000-00010.
22. Hernandez RJ, Tachdjian MO, Poznanski AK, et al. CT determination of femoral torsion. AJR Am J Roentgenol. 1981; 137(1): 97-101. doi: 10.2214/ajr.137.1.97.
23. Jarrett DY, Oliveira AM, Zou KH, et al. Axial oblique CT to assess femoral anteversion. AJR Am J Roentgenol. 2010; 194(5): 1230-3. doi: 10.2214/AJR.09.3702.
24. Peck CN, Childs J, McLauchlan GJ. Inferior outcomes of total knee replacement in early radiological stages of osteoarthritis. Knee. 2014; 21(6): 1229-32. doi: 10.1016/j.knee.2014.08.018.
25. Link TM, Majumdar S, Lin JC, et al. A comparative study of trabecular bone properties in the spine and femur using high resolution MRI and CT. J Bone Miner Res. 1998; 13(1): 122-32. doi: 10.1359/jbmr.1998.13.1.122.
26. Karol LA. Rotational deformities in the lower extremities. Curr Opin Pediatr. 1997; 9(1): 77-80. doi: 10.1097/00008480-199702000-00016.
27. Branca Vergano L, Coviello G, Monesi M. Rotational malalignment in femoral nailing: prevention, diagnosis and surgical correction. Acta Biomed. 2020; 91(14-S): e2020003. doi: 10.23750/abm.v91i14-S.10725.
28. Passmore E, Graham HK, Sangeux M. Defining the medial-lateral axis of the femur: Medical imaging, conventional and functional calibration methods lead to differences in hip rotation kinematics for children with torsional deformities. J Biomech. 2018; 69: 156-63. doi: 10.1016/j.jbiomech.2018.01.018.
29. Hughes A, Heidari N, Mitchell S, et al. Computer hexapod-assisted orthopaedic surgery provides a predictable and safe method of femoral deformity correction. Bone Joint J. 2017; 99-B(2): 283-8. doi: 10.1302/0301-620X.99B2.BJJ-2016-0271.R1.
30. Mayr HO, Schmidt JP, Haasters F, et al. Anteversion Angle measurement in suspected torsional malalignment of the femur in 3-Dimensional EOS vs computed tomography-a validation study. J Arthroplasty. 2021; 36(1): 379-386. doi: 10.1016/j.arth.2020.07.058.
31. Marx RG, Grimm P, Lillemoe KA, et al. Reliability of lower extremity alignment measurement using radiographs and PACS. Knee Surg Sports Traumatol Arthrosc. 2011; 19(10): 1693-8. doi: 10.1007/s00167-011-1467-3.
32. Edmonds EW, Parvaresh KC, Price MJ, et al. The reliability of measurements for tibial torsion: a comparison of CT, MRI, biplanar radiography, and 3D reconstructions with and without standardized measurement training. J Pediat Orthop Soc North Am. 2023; 5(3): 661. doi: 10.55275/JPOSNA-2023-661.
33. Frizziero L, Trisolino G, Santi GM, et al. Computer-aided surgical simulation through digital dynamic 3D skeletal segments for correcting torsional deformities of the lower limbs in children with cerebral palsy. Appl Sci. 2022; 12(15): 7918. doi: 10.3390/app12157918.
34. Feng J, Wick J, Bompiani E, et al. Applications of gait analysis in pediatric orthopaedics. Curr Orthop Pract. 2016; 27(4): 455-64. doi: 10.1097/BCO.0000000000000384.
35. Shih YC, Chau MM, Arendt EA, et al. Measuring lower extremity rotational alignment: a review of methods and case studies of clinical applications. J Bone Joint Surg Am. 2020; 102(4): 343-56. doi: 10.2106/JBJS.18.01115.
36. Skinner HB, Effeney DJ. Gait analysis in amputees. Am J Phys Med. 1985; 64(2): 82-9.
37. Schröter S, Elson DW, Ateschrang A, et al. lower limb deformity analysis and the planning of an osteotomy. J Knee Surg. 2017; 30(5): 393-408. doi: 10.1055/s-0037-1603503.
38. Specogna AV, Birmingham TB, DaSilva JJ, et al. Reliability of lower limb frontal plane alignment measurements using plain radiographs and digitized images. J Knee Surg. 2004; 17(4): 203-10. doi: 10.1055/s-0030-1248222.
39. Oraa J, Fiz N, González S, et al. Derotation tibial osteotomy with custom cutting guides and custom osteosynthesis plate printed with 3D technology: Case and technical note. Ann 3D Printed Med. 2023; 9: 100093. doi: https://doi.org/10.1016/j.stlm.2022.100093.
40. Brouwer GM, van Tol AW, Bergink AP, et al. Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis Rheum. 2007; 56(4): 1204-11. doi: 10.1002/art.22515.
41. Popkov D, Journeau P, Popkov A, et al. Analysis of segmental residual growth after progressive bone lengthening in congenital lower limb deformity. Orthop Traumatol Surg Res. 2012; 98(6): 621-8. doi: 10.1016/j.otsr.2012.06.012.
42. Marti CB, Gautier E, Wachtl SW, et al. Accuracy of frontal and sagittal plane correction in open-wedge high tibial osteotomy. Arthroscopy. 2004; 20(4): 366-72. doi: 10.1016/j.arthro.2004.01.024.
43. Macewen W. Antiseptic osteotomy in genu valgum and anterior tibial curves: With a few remarks on the

pathology of knock-knee. Br Med J. 1879; 2(981): 607-9. doi: 10.1136/bmj.2.981.607.

44. Cooke TD, Li J, Scudamore RA. Radiographic assessment of bony contributions to knee deformity. Orthop Clin North Am. 1994; 25(3): 387-93.
45. Pape D, Rupp S. Preoperative planning for high tibial osteotomies. Oper Tech Orthop. 2007; 17(1): 2-11. doi: https://doi.org/10.1053/j.oto.2006.09.007.
46. McVeigh KH, Murray PM, Heckman MG, et al. Accuracy and validity of goniometer and visual assessments of angular joint positions of the hand and wrist. J Hand Surg Am. 2016; 41(4): e21-35. doi: 10.1016/j.jhsa.2015.12.014.
47. Mündermann A. Use of Anthropometry for the Measurement of lower extremity alignment. In: Preedy VR (ed). Handbook of anthropometry: Physical Measures of human form in health and disease. Springer; 2012. p. 2951-70.
48. Müller M, Strecker W. Arthroscopy prior to osteotomy around the knee? Arch Orthop Trauma Surg. 2008; 128(11): 1217-21. doi: 10.1007/s00402-007-0398-4.
49. Maderbacher G, Schaumburger J, Baier C, et al. Predicting knee rotation by the projection overlap of the proximal fibula and tibia in long-leg radiographs. Knee Surg Sports Traumatol Arthrosc. 2014; 22(12): 2982-8. doi: 10.1007/s00167-014-3327-4.
50. Roggio F, Ravalli S, Maugeri G, et al. Technological advancements in the analysis of human motion and posture management through digital devices. World J Orthop. 2021; 12(7): 467-84. doi: 10.5312/wjo.v12.i7.467.
51. Christensen R, Petersen ET, Jürgens-Lahnstein J, et al. Assessment of knee kinematics with dynamic radiostereometry: Validation of an automated model-based method of analysis using bone models. J Orthop Res. 2021; 39(3): 597-608. doi: 10.1002/jor.24875.
52. Tannous H, Istrate D, Benlarbi-Delai A, et al. A new multi-sensor fusion scheme to improve the accuracy of knee flexion kinematics for functional rehabilitation movements. Sensors (Basel). 2016; 16(11): 1914. doi: 10.3390/s16111914.
53. Bråten M, Terjesen T, Rossvoll I. Torsional deformity after intramedullary nailing of femoral shaft fractures. Measurement of anteversion angles in 110 patients. J Bone Joint Surg Br. 1993; 75(5): 799-803. doi: 10.1302/0301-620X.75B5.8376444.
54. Frizziero L, Santi GM, Liverani A, et al. Computer-aided surgical simulation for correcting complex limb deformities in children. Appl Sci. 2020; 10(15): 5181. doi: https://doi.org/10.3390/app10155181.
55. Daggett SM, Cantarelli T, Gyftopoulos S, et al. Cost-effectiveness Analysis in Diagnostic Musculoskeletal Radiology: A Systematic Review. Curr Probl Diagn Radiol. 2023; 52(1): 20-4. doi: 10.1067/j.cpradiol.2022.07.003.
56. McCoy M, Campbell I, Stone P, et al. Intra-examiner and inter-examiner reproducibility of paraspinal thermography. PLoS One. 2011; 6(2): e16535. doi: 10.1371/journal.pone.0016535.

Stanley JC, Robinson KG, Devitt BM, et al. Computer assisted alignment of opening wedge high tibial osteotomy provides limited improvement of radiographic outcomes compared to flouroscopic alignment. Knee. 2016; 23(2): 289-94. doi: 10.1016/j.knee.2015.12.006.

57. Hafiz E, Hiller CE, Nicholson LL, et al. Development of a method for measuring femoral torsion using real-time ultrasound. Physiol Meas. 2014; 35(7): 1335-48. doi: 10.1088/0967-3334/35/7/1335.
58. Sarikaya IA, Seker A, Erdal OA, et al. Minimally invasive plate osteosynthesis for tibial derotation osteotomies in children with cerebral palsy. Acta Orthop Traumatol Turc. 2018; 52(5): 352-6. doi: 10.1016/j.aott.2018.02.003.
59. Seil R, van Heerwaarden R, Lobenhoffer P, et al. The rapid evolution of knee osteotomies. Knee Surg Sports Traumatol Arthrosc. 2013; 21(1): 1-2. doi: 10.1007/s00167-012-2175-3.
60. Brühschwein A, Schmitz B, Zöllner M, et al. Computed tomographic angular measurements using a bone-centered three-dimensional coordinate system are accurate in a femoral torsional deformity model and precise in clinical canine patients. Front Vet Sci. 2023; 10: 1019216. doi: 10.3389/fvets.2023.1019216.
61. Pawik Ł, Pawik M, Wrzosek Z, et al. Assessment of the quality of life in patients with varying degrees of equalization of lower limb length discrepancy treated with Ilizarov method. J Orthop Surg Res. 2021; 16(1): 62. doi: 10.1186/s13018-021-02202-1.
62. Gajdosik RL, Bohannon RW. Clinical measurement of range of motion. Review of goniometry emphasizing reliability and validity. Phys Ther. 1987; 67(12): 1867-72. doi: 10.1093/ptj/67.12.1867.
63. Mutlu A, Livanelioglu A, Gunel MK. Reliability of goniometric measurements in children with spastic cerebral palsy. Med Sci Monit. 2007; 13(7): CR323-9.
64. Siapno AED, Yi BC, Daniels D, et al. Measurement accuracy of 3-Dimensional mapping technologies versus standard goniometry for angle assessment. J Pediatr Urol. 2020; 16(5): 547-54. doi: 10.1016/j.jpurol.2020.08.021.
65. Marques Luís N, Varatojo R. Radiological assessment of lower limb alignment. EFORT Open Rev. 2021; 6(6): 487-94. doi: 10.1302/2058-5241.6.210015.
66. Kim TY, Lee YB, Chang JD, et al. Torsional malalignment, how much significant in the trochanteric fractures? Injury. 2015; 46(11): 2196-200. doi: 10.1016/j.injury.2015.07.015.
67. Hansen L, De Raedt S, Jørgensen P, et al. Marker free model-based radiostereometric analysis for evaluation of hip joint kinematics: A validation study. Bone Joint Res. 2018; 7(6): 379-87. doi: 10.1302/2046-3758.76.bjr-2017-0268.r1.
68. De Groote F, Falisse A. Perspective on musculoskeletal modelling and predictive simulations of human movement to assess the neuromechanics

of gait. Proc Biol Sci. 2021; 288(1946): 20202432. doi: 10.1098/rspb.2020.2432.

69. Kaiser P, Attal R, Kammerer M, et al. Significant differences in femoral torsion values depending on the CT measurement technique. Arch Orthop Trauma Surg. 2016; 136(9): 1259-64. doi: 10.1007/s00402-016-2536-3.

70. Moldovan F, Gligor A, Bataga T. Integration of three-dimensional technologies in orthopedics: a tool for preoperative planning of tibial plateau fractures. Acta Inform Med. 2022; 28(4): 278-82. doi: 10.5455/aim.2020.28.278-282.

71. Stephen JM, Teitge RA, Williams A, et al. A validated, automated, 3-dimensional method to reliably measure tibial torsion. Am J Sports Med. 2021; 49(3): 747-56. doi: 10.1177/0363546520986873.

72. Berhouet J, Samargandi R. Emerging innovations in preoperative planning and motion analysis in orthopedic surgery. Diagnostics (Basel). 2024; 14(13): 1321. doi: 10.3390/diagnostics14131321.

73. Carter SL, Duncan R, Weidemann AL, et al. Lower leg and foot contributions to turnout in female pre-professional dancers: A 3D kinematic analysis. J Sports Sci. 2018; 36(19): 2217-25. doi: 10.1080/02640414.2018.1446386.

74. Christiansen JD, Ejaz A, Nielsen PT, et al. An ultra-short femoral neck-preserving hip prosthesis: A 2-year follow-up study with radio stereometric analysis and dual x-ray absorptiometry in a stepwise introduction. J Bone Joint Surg Am. 2020; 102(2): 128-36. doi: 10.2106/JBJS.19.00104.

75. Chhaily ZA, Joda AI, Hafith AA, et al. Radiological and clinical results of pemberton osteotomy for delayed presentation of iraqi ddh patients. Iraqi J Med Sci. 2021; 19(2): 182-8. doi: 10.22578/IJMS.19.2.7.

76. Ali WQ, Selman MO, Al-Hasson IJ, et al. The effects of dexamethasone on tibia development of local chick-embryo. I: Computer-assisted morphometric study. Iraqi J Med Sci. 2017; 15(2): 116-28. doi: 10.22578/IJMS.15.2.3.

Correspondence to Batool A. Akar

E-mail: batool.mbe23@ced.nahrainuniv.edu.iq

Received Feb. 13th 2025

Accepted May 25th 2025