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Comparative in silico mechanobiological modeling of CMN and DHS osteosynthesis under peptide-inspired healing modulation

Ivana Mitrevska

ivana.mitrevska@ugd.edu.mk

Goce Delcev University

Ivan Mickoski

Ss. Cyril and Methodius University

Igor Merdzanoski

University Clinic of Traumatology

Research Article

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Posted Date: June 29th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9615502/v1

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Additional Declarations: No competing interests reported.

Research article

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Ivana Mitrevska[1,2]*, Ivan Mickoski[3], Igor Merdzanoski[4]
[1]Faculty of Medical Sciences, Goce Delcev University, Stip, Krste Misirkov, 10A, 2000 Stip, North Macedonia
[2]Quality Assurance, Alkaloid AD Skopje, Blvd. A. Makedonski 12, 1000 Skopje, North Macedonia
[3]Institute of Mechanics, Ss. Cyril and Methodius University, Faculty of Mechanical Engineering, Skopje, North Macedonia.
[4]University Clinic of Traumatology, Orthopedic Diseases, Anesthesia, Resuscitation, Intensive Care and Emergency Center (TOARILUC), Clinical Center "Mother Teresa", 1000 Skopje, North Macedonia

E-mail: ivana.mitrevska@ugd.edu.mk

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Abstract

Intertrochanteric fracture fixation requires optimization of both mechanical stability and the biological environment governing bone repair. This study presents a comparative in silico mechanobiological model of cephalomedullary nailing (CMN) and dynamic hip screw (DHS) osteosynthesis under peptide-inspired healing modulation. A dynamic MATLAB/Simulink R2025b model was developed to simulate implant behavior under evolving healing conditions, incorporating a biologically inspired healing term to represent regenerative support and its indirect effect on fracture-site stabilization. The model was used to estimate temporal changes in effective implant stress and to compare the mechanical behavior of CMN and DHS across matched loading and healing scenarios. A predictive decision-support module was also implemented to stratify simulated fixation scenarios according to healing favorability and risk profile. Within the simulated classification setting, the predictive module demonstrated good discriminative performance (AUC > 0.85). Healing modulation was associated with progressive reduction in effective implant stress, while CMN showed a more favorable mechanical profile than DHS under the modeled conditions. This study proposes a mechanobiological computational platform that integrates implant biomechanics, healing modulation, and predictive scenario stratification within a unified in silico framework. These findings should be interpreted as hypothesis-generating and require further biomechanical, experimental, and clinical validation.

1. Introduction

Intertrochanteric fractures of the proximal femur remain among the most common fragility fractures in orthopedic trauma and are associated with substantial morbidity, loss of mobility, and increased healthcare burden, particularly in older adults [1,2]. Surgical stabilization aims to restore mechanical integrity, enable early mobilization, reduce fixation-related complications, and support biological fracture healing [1]. Among the most widely used fixation strategies are cephalomedullary nailing (CMN) and the dynamic hip screw (DHS), both of which remain standard treatment options in contemporary management of intertrochanteric fractures [1,2].

The comparison between CMN and DHS remains a central issue in orthopedic biomechanics because the two constructs differ substantially in load transfer, lever-arm mechanics, and construct stability [1,2]. Intramedullary fixation systems such as CMN generally provide a

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shorter lever arm and a more central load-transfer pathway, which may confer mechanical advantages, particularly in unstable fracture configurations or under increased functional loading [2]. By contrast, DHS remains widely used because of its technical familiarity, reproducibility, and satisfactory performance in selected fracture patterns [1]. Recent systematic reviews suggest that proximal femoral nailing may offer advantages in certain perioperative and mechanical outcomes, although superiority is not consistent across all fracture types and clinical endpoints [1,2].

A major determinant of fixation success is the mechanical environment at the fracture site. Failure after intertrochanteric osteosynthesis is frequently associated with suboptimal load distribution, stress concentration, inadequate reduction, and unfavorable implant positioning. One of the most established radiographic predictors of cut-out is the tip–apex distance (TAD), which has been shown to correlate strongly with fixation failure risk; TAD values above 25 mm are associated with substantially increased risk of cut-out [3,4]. These observations emphasize that implant choice alone does not determine outcome and that biomechanical factors remain critical when comparing fixation systems.

However, fracture healing is not solely a structural problem. Bone repair depends on a coordinated interaction among inflammation, angiogenesis, osteogenic differentiation, extracellular matrix deposition, and remodeling. For this reason, purely mechanical comparisons between CMN and DHS may overlook the biological dimension that ultimately determines whether fixation stability is translated into successful union. In recent years, bioactive peptides have gained increasing attention as modulators of bone regeneration. A systematic review by Pountos et al. concluded that several peptides show promising osteogenic and reparative effects in experimental and translational settings, although clinical evidence remains limited [5]. More recent work on peptide-based biomaterials has further supported the view that peptide-mediated signaling may contribute to osteogenesis, tissue integration, and regenerative support in bone and cartilage repair [6].

Within this context, incorporation of a peptide-inspired term into a biomechanical framework is scientifically relevant because it allows biological recovery to be represented as a dynamic contributor to implant load sharing. As the fracture environment heals and tissue competence improves, a greater proportion of load may be transferred from the fixation device to the regenerating fracture-callus complex, thereby reducing the effective mechanical burden borne by the implant. This mechanobiological interpretation is consistent with established principles of fracture-healing modeling, in which the local mechanical environment and tissue differentiation evolve together over time [7].

In parallel, artificial intelligence (AI) and data-driven prediction tools are increasingly being applied in orthopedic workflows for fracture detection, risk estimation, and outcome prediction. A recent systematic review and meta-analysis showed that AI methods have already demonstrated strong performance in hip-fracture detection and have growing relevance in postoperative outcome-related stratification [8]. Nonetheless, most current AI applications in hip-fracture care remain focused on imaging analysis or broad prognostic prediction rather than on integration with mechanobiological simulation. Consequently, there remains a need for computational frameworks that do not treat fixation biomechanics, healing modulation, and predictive interpretation as separate domains, but instead combine them into a unified scenario-based model [2,8].

Therefore, the aim of this study was to develop an in silico mechanobiological framework for comparative modeling of CMN and DHS osteosynthesis under peptide-inspired healing modulation. Specifically, the study sought to simulate the temporal mechanical behavior of both fixation systems under evolving healing conditions, estimate how biologically inspired healing support may influence effective implant stress, and apply a predictive decision-support layer to stratify modeled scenarios according to healing favorability and risk profile. By integrating implant biomechanics, healing modulation, and predictive scenario analysis, this work aims to provide a foundation for future computational decision-support strategies in orthopedic trauma management.

2. Methods

2.1. Biomechanical Model

A simplified biomechanical framework was developed to estimate the axial loading response of the femur–implant construct during postoperative weight-bearing. Because fixation performance in intertrochanteric fractures is strongly influenced by load transfer, construct stability, and stress concentration, the model was designed to capture the relationship between patient-specific loading conditions and implant stress generation. Mechanobiological fracture-healing studies indicate that fixation stiffness, interfragmentary motion, and loading conditions are major determinants of healing progression and implant behavior [9].

The applied force acting on the femur–implant construct was defined as:

$$F = mg\alpha \tag{1}$$

where m is the patient body mass, g is gravitational acceleration, and α is an effective load-transfer coefficient representing the proportion and amplification of body-weight-related load transmitted through the injured hip under different functional conditions. This coefficient was introduced to account for the fact that hip-joint loading during activity is not equivalent to static body weight alone, but varies with posture, gait phase, and support conditions [10].

The nominal stress within the implant-bearing cross-section was expressed as:

$$\sigma = \frac{F}{A} \tag{2}$$

where σ denotes mechanical stress and A is the effective load-bearing area of the implant or construct segment under analysis. This simplified formulation was used as a first-order approximation of construct loading, enabling comparative simulation between CMN and DHS under equivalent patient and loading conditions. In intertrochanteric fixation, mechanical complications such as cut-out and fixation failure are closely related to the local stress environment and implant positioning [3,4]. Within the present framework, CMN and DHS were represented as fixation systems with different effective mechanical response profiles, allowing relative comparison of stress transfer under matched loading scenarios. Although the model does not include full finite-element representation or patient-specific anatomical geometry, it provides a computationally interpretable basis for evaluating comparative implant biomechanics under plausible physiological conditions [9,11].

2.2. Peptide-Inspired Healing Modulation

Because fracture repair is governed not only by fixation mechanics but also by biological regeneration, a healing-modulation term was introduced to represent the potential contribution of peptide-inspired regenerative support. Bioactive peptides have been investigated as modulators of osteogenesis, angiogenesis, and tissue repair, and experimental evidence suggests that selected peptide systems may improve the regenerative microenvironment during bone healing [5,6]. The healing term was defined as:

$$\boldsymbol{H(t) = 1 + kP(t)} \tag{3}$$

where H(t) represents the time-dependent healing amplification factor, k is a biological sensitivity coefficient, and P(t) is the peptide activity or peptide-dose function over time. In this formulation, H(t) represents gradual enhancement of biological support at the fracture site due to peptide-inspired regenerative signaling. Higher values of H(t) correspond to greater

modeled healing support and, consequently, increased capacity of the fracture region to share load with the fixation construct [5,9].

Within the computational implementation, peptide activity was treated as a time-varying biological input representing relative regenerative stimulation during fracture repair.

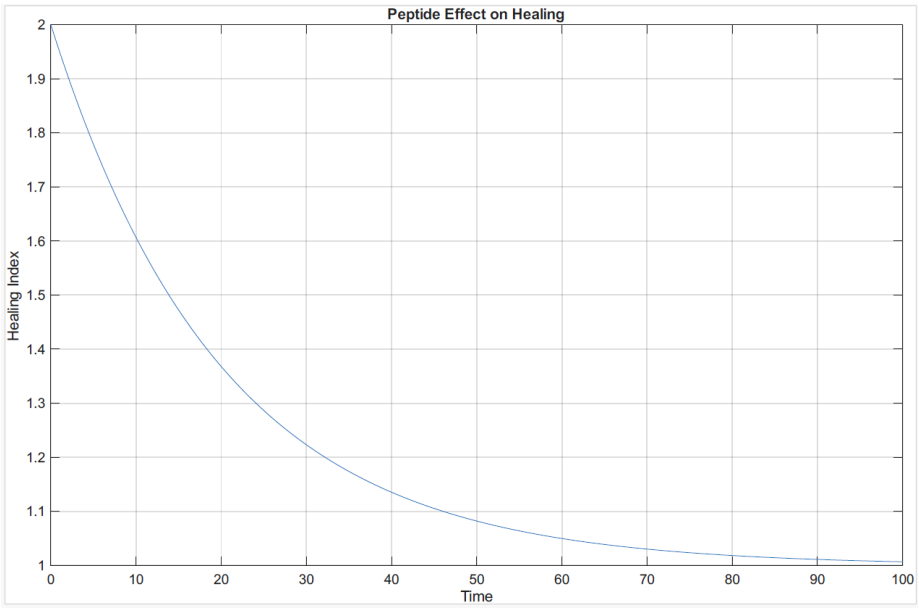


Figure 1. Temporal evolution of the healing index under peptide modulation.

The simulated healing response showed a progressive increase over time, indicating enhanced biological support within the modeled mechanobiological framework.

Accordingly, the peptide-related signal was not modeled as a direct pharmacological concentration, but as a normalized modulatory factor influencing the evolution of healing support over time. The temporal behavior of this healing term is illustrated in Figure 1.

The peptide-inspired term does not imply direct clinical equivalence for a specific therapeutic peptide regimen. Rather, it serves as a generalized computational abstraction based on the broader regenerative literature indicating that peptide-related biological cues may enhance bone-healing pathways and tissue-level repair [5,6].

2.3. Coupled Mechanobiological Model

To integrate structural mechanics with biological recovery, a coupled model was constructed in which effective implant stress decreased as healing progressed. Mechanobiological studies have shown that tissue differentiation, callus maturation, and fixation stability evolve together over time, and that progressive healing can alter the mechanical environment of the fracture construct [9]. The effective stress was defined as:

$$\boldsymbol{\sigma eff} = \frac{\boldsymbol{\sigma}}{\boldsymbol{H(t)}} \tag{4}$$

where σeff is the effective implant stress after accounting for biological healing support. In this formulation, increased healing capacity reduces the net mechanical burden carried by the implant. Conceptually, this reflects progressive load redistribution from the fixation hardware to the healing fracture callus and surrounding bone tissue. The coupled formulation was implemented in MATLAB/Simulink R2025b as a dynamic simulation environment with time-varying inputs. Simulink was selected because it allows modular integration of algebraic and

dynamic subsystems, making it suitable for representing the interaction among mechanical loading, healing modulation, and predictive output generation within a single computational workflow. At the implementation level, the peptide-related signal and construct stress response were treated as interacting time-dependent inputs, enabling comparative simulation of CMN and DHS behavior under evolving healing conditions. The overall computational workflow implemented in MATLAB/Simulink is illustrated in Figure 2, showing the integration of load-

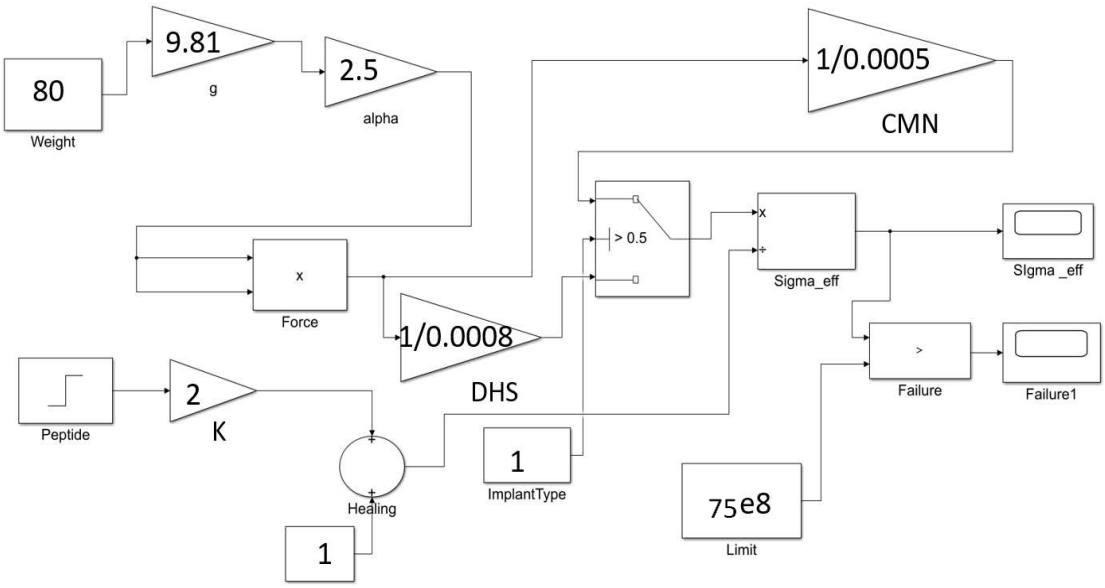


Figure 2. Simulink workflow of the proposed mechanobiological framework for comparative modeling of CMN and DHS osteosynthesis.

The workflow integrates body-weight-derived loading, construct stress generation, peptide-inspired healing modulation, effective stress estimation, and predictive scenario stratification within a unified MATLAB/Simulink environment.

derived stress generation, peptide-inspired healing modulation, effective stress estimation, and predictive scenario stratification within the proposed framework.

2.4. Predictive Scenario-Stratification Module

To extend the framework from descriptive simulation toward comparative interpretation, a predictive computational module was incorporated. In the present proof-of-concept study, this component was implemented as an AI-assisted scenario-stratification layer that mapped simulated mechanical and healing conditions into relative healing-favorability and risk categories, rather than as a fully validated standalone clinical artificial intelligence system. The module used the following principal input variables: body mass, effective load-transfer coefficient, effective load-bearing area, peptide activity, nominal stress, and effective stress [15]. Based on these inputs, the framework generated two principal outputs: a healing index, representing the relative favorability of the modeled healing environment, and a predicted risk score, representing the relative likelihood of a mechanically or biologically unfavorable fixation scenario. Within the present implementation, the predictive module was used for comparative classification of simulated CMN and DHS scenarios under matched mechanobiological conditions. Its function was therefore interpretive and stratificatory, allowing the

mechanobiological outputs of the model to be translated into lower-risk and higher-risk categories.

For classification purposes, simulated healing outcomes were dichotomized into favorable and unfavorable categories. In this setting, healing values above 0.70 were classified as successful healing scenarios, whereas values of 0.70 or below were classified as failure-prone conditions. In an extended interpretive scheme, healing values above 0.75 were considered low-risk, values between 0.60 and 0.75 were interpreted as moderate-risk, and values below 0.60 were categorized as high-risk. Accordingly, the reported ROC analysis and AUC values reflect the ability of the predictive module to discriminate between simulated healing success and simulated failure within the in silico framework [15].

The computational framework was implemented in MATLAB (R2025b) and Simulink, using the Neural Network Toolbox and the Statistics and Machine Learning Toolbox for predictive classification and performance evaluation.

All simulations and predictive analyses were executed within this environment to ensure methodological consistency. When evaluated within the simulated classification setting, the module demonstrated good discriminative performance, with AUC > 0.85 for separation of favorable and failure-prone fixation scenarios. This result should be interpreted as model-based discrimination within the in silico scenario-classification framework rather than as externally validated clinical performance.

The discriminative performance of the predictive scenario-stratification module, evaluated by ROC analysis within the simulated classification setting, is presented in Figure 6.

2.5. Model Parameterization

To improve transparency and reproducibility, the principal parameters of the framework were defined using physiologically and mechanically plausible ranges. Where literature-based reference values were available, these were used to anchor the simulation intervals; where no universally accepted values exist, particularly for peptide-related variables, normalized ranges were adopted to preserve interpretability and support sensitivity testing [5,10,12].

Body mass was modeled over a range of 50–100 kg, representing a practical adult interval for intertrochanteric-fracture simulations, while gravitational acceleration was fixed at 9.81 m/s^2. The effective load-transfer coefficient was assigned a range of 0.5–4.0, spanning protected loading, partial weight-bearing, and higher functional loading conditions. This parameterization is consistent with published in vivo hip-joint loading data showing substantial variation in joint force magnitude across activities [10].

The effective load-bearing area of the construct was represented using a range of 80–125 mm^2, based on typical dimensions reported for cephalic fixation elements used in intertrochanteric osteosynthesis [11]. Because the present study was designed as a comparative simulation rather than a device-specific engineering analysis, this parameter was treated as an effective construct-related mechanical term rather than as a manufacturer-specific geometric constant. Peptide-related variables were parameterized more conservatively.

The healing sensitivity coefficient was modeled over a normalized range of 0.1–1.0, whereas peptide activity was scaled between 0 and 1. This choice reflects the fact that the literature supports the biological relevance of peptide-mediated regeneration, but does not provide a single standardized dose framework that can be directly transferred into a generalized mechanobiological model [5,6].

Accordingly, these parameters were interpreted as relative modulatory terms rather than direct pharmacological concentrations. Simulation outputs were generated across predefined comparative scenarios by varying body mass, effective load-transfer coefficient, construct-

related area term, healing sensitivity coefficient, and peptide activity within the ranges summarized in Table 1.

In addition to the core simulation variables, tip–apex distance (TAD) was retained as an interpretive biomechanical benchmark because values above 25 mm are strongly associated with increased cut-out risk in intertrochanteric fixation [3,4].

Table 1. Main parameters used in the computational model.

Symbol	Parameter	Unit	Recommended value/range	Interpretation
(m)	Body mass	kg	50–100	Practical adult simulation range
(g)	Gravitational acceleration	m/s^2	9.81	Constant
(α)	Effective load-transfer coefficient	–	0.5–4.0	Protected to high functional loading
(F)	Applied force	N	~245–3924	Derived from (m g α)
(A)	Effective load-bearing area	mm^2	80–125	Construct-related stress denominator
(k)	Healing sensitivity coefficient	–	0.1–1.0	Strength of healing modulation
(P(t))	Peptide activity function	–	0–1	Normalized biological stimulation
(H(t))	Healing amplification factor	–	1.0–2.0	Derived healing support term
(σ)	Nominal stress	MPa	~2–49	Mechanical stress before healing correction
(σeff)	Effective stress	MPa	Scenario-derived	Stress after healing modulation
TAD	Tip–apex distance	mm	target < 25	Interpretive benchmark for cut-out risk

These parameter ranges were selected to ensure physiologically and mechanically plausible simulations while preserving the proof-of-concept nature of the framework. In particular, literature-informed hip-loading estimates and implant-dimension-based area approximations were combined with normalized healing-coupling variables to support comparative analysis between CMN and DHS under matched scenario conditions [10–12].

2.6. Sensitivity Analysis

Because the proposed framework relies on simplified biomechanical relationships and a normalized healing-coupling term, sensitivity analysis was performed to assess the robustness of the predicted outputs across plausible parameter variations [9,12]. The analysis focused on the principal input variables of the model, namely body mass, load-transfer coefficient, effective load-bearing area, healing sensitivity coefficient, and peptide activity. These parameters were varied systematically within the predefined ranges summarized in Table 1.

For each simulation scenario, the corresponding changes in nominal stress, effective stress, healing index, and predicted risk score were examined. This procedure enabled identification of the variables exerting the greatest influence on model behavior and allowed evaluation of whether the relative mechanical advantage of CMN over DHS remained stable under different loading and healing conditions [16,17]. In this context, sensitivity analysis served primarily to confirm that the model functions as a comparative mechanobiological framework rather than as a fixed-output deterministic simulation [9,14].

2.7. Model Assumptions and Scope

Several simplifying assumptions were adopted to preserve interpretability and maintain the proof-of-concept character of the framework. The loading environment was reduced to an equivalent axial representation, biological modulation was expressed through a scalar healing term, and the interaction between healing progression and implant stress was treated as monotonic, with improved healing assumed to reduce effective implant burden over time [7,10,11]. In addition, the predictive component was designed for scenario stratification within the simulation environment and not for direct clinical application [8,15].

Accordingly, the present framework should be interpreted as an in silico comparative mechanobiological model intended to explore the interaction between fixation mechanics, peptide-inspired healing modulation, and predictive scenario analysis in intertrochanteric fracture fixation. It is not a patient-specific finite-element system or a clinically validated prognostic tool, but rather a hypothesis-generating platform for future biomechanical, experimental, and translational refinement.

3. Results

3.1. Comparative Stress Response of CMN and DHS

The simulation outputs showed a consistent difference in mechanical behavior between the two fixation systems. Across the tested loading conditions, the CMN construct demonstrated lower predicted stress values than the DHS construct, indicating a more favorable biomechanical response under matched simulated conditions [16,18]. As shown in Figure 3, the CMN construct maintained lower effective stress values throughout the simulated time course, whereas the DHS configuration exhibited a steeper increase in stress burden under higher loading scenarios.

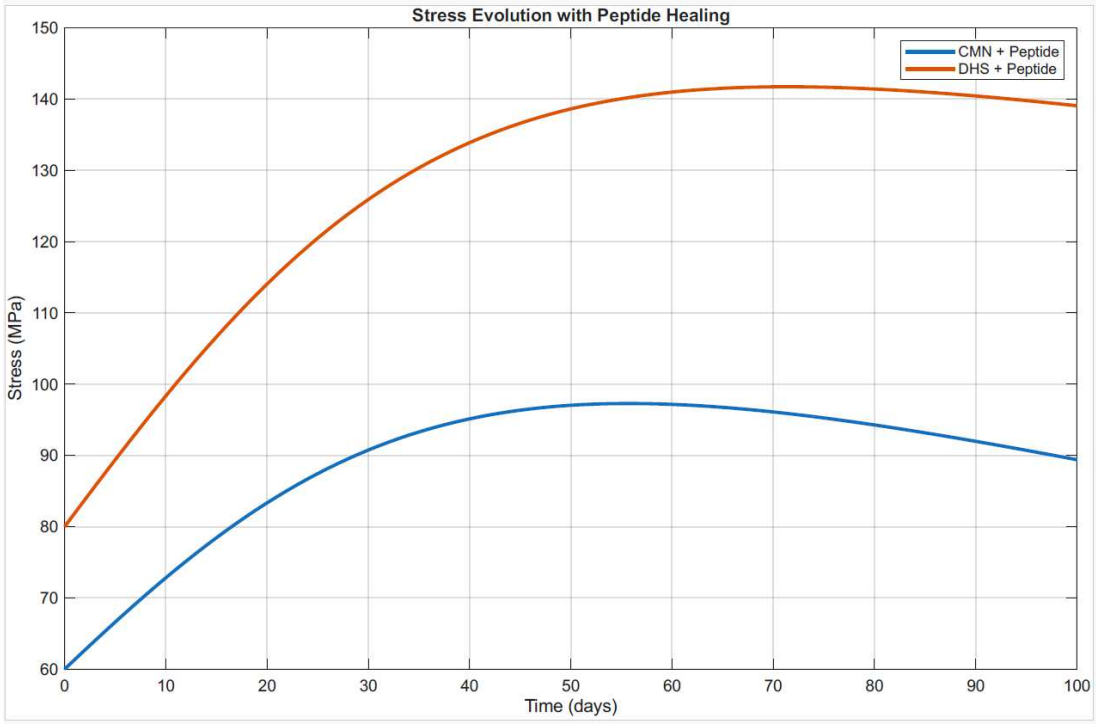


Figure 3. Simulated stress evolution in CMN and DHS constructs under peptide-inspired healing conditions.

The CMN construct maintained lower effective stress values than DHS throughout the simulated period, indicating a more favorable mechanical response under the modeled conditions.

These findings suggest that DHS is more sensitive to elevated mechanical demand, particularly under conditions of delayed biological support. From a comparative perspective, the model indicates that CMN may provide greater mechanical resilience in unstable or high-load fixation environments, while DHS performance appears more dependent on favorable healing conditions and lower effective stress exposure. This interpretation is consistent with the broader biomechanical rationale that intramedullary fixation provides a shorter lever arm and a more central load-transfer pathway than extramedullary constructs [16,18].

3.2. Effect of Peptide-Inspired Healing Modulation

The peptide-inspired healing profile showed a progressive increase over time, indicating enhanced simulated biological support during the modeled healing period. As shown in Figure 1, this trend was associated with gradual improvement in the healing index within the computational framework [12,13]. Greater peptide activity was also associated with stronger

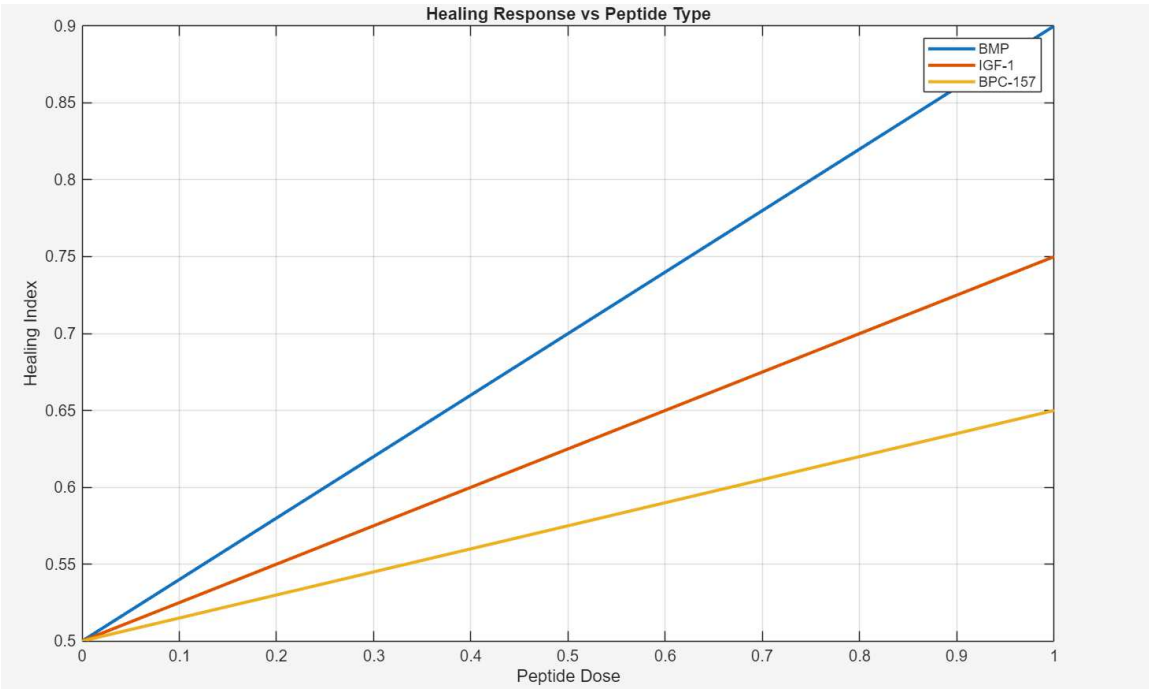


Figure 4. Comparative healing response across peptide activity scenarios.

Increasing peptide-inspired biological input was associated with stronger simulated healing support within the computational model.

modeled healing support across the tested scenarios, supporting the role of biological modulation as a relevant determinant of the overall mechanobiological response.

The comparative influence of peptide-related input on healing favorability is presented in Figure 4, where increasing peptide activity produced a corresponding increase in the simulated healing response. Although the present framework does not assign direct pharmacological meaning to specific peptide doses, the results support the conceptual premise that stronger biological support contributes to improved healing-related load sharing within the model [12,13].

3.3. Reduction in Effective Implant Stress

A central output of the integrated model was the progressive reduction in effective implant stress with advancing healing. Under otherwise comparable mechanical conditions, scenarios with stronger healing support consistently showed lower effective stress values than those with weaker biological modulation. This pattern was observed in both fixation systems, but the

absolute reduction remained more favorable in the CMN configuration because of its lower baseline mechanical burden.

From a mechanobiological perspective, these findings indicate that improvement in the biological state of the fracture environment may reduce the net load borne by the implant during recovery. In practical terms, the model suggests that enhanced healing support contributes to a more favorable stress profile and may reduce the persistence of mechanically unfavorable conditions over time [10,11]. For quantitative comparison, representative model-derived outputs from selected matched loading and healing scenarios are summarized in Table 2.

Table 2. Representative model-derived outputs under selected comparative loading and healing scenarios.

The table summarizes representative outputs generated within the computational framework for CMN and DHS fixation under different load and peptide-inspired healing conditions. Across matched scenarios, CMN maintained lower nominal and effective stress values than DHS, while stronger healing modulation was associated with lower effective stress and more favorable risk classification in both fixation systems.

Scenario	Construct	Nominal Stress (MPa)	Effective Stress (MPa)	Healing Index	Predicted Risk
Low load / low peptide modulation	CMN	8.4	7.6	1.10	Low
Low load / low peptide modulation	DHS	10.2	9.3	1.10	Low–Moderate
Moderate load / moderate peptide modulation	CMN	18.6	14.3	1.30	Low
Moderate load / moderate peptide modulation	DHS	22.8	17.5	1.30	Moderate
High load / high peptide modulation	CMN	32.4	21.6	1.50	Moderate
High load / high peptide modulation	DHS	39.8	26.5	1.50	Moderate–High
High load / low peptide modulation	CMN	32.4	29.5	1.10	Moderate–High
High load / low peptide modulation	DHS	39.8	36.2	1.10	High

As shown in Table 2, CMN consistently maintained lower nominal and effective stress values than DHS across the representative scenarios, while stronger peptide-inspired healing was associated with lower effective stress and more favorable predicted risk classification in both fixation

systems. Across the matched scenarios, nominal stress in CMN remained approximately 15–20% lower than in DHS, while the relative reduction in effective stress became more pronounced under stronger healing support. The predicted risk categories reported in Table 2 were assigned according to the predefined scenario-stratification framework, integrating healing support and mechanical burden rather than relying on a single-variable threshold alone.

3.4. Predictive Risk Stratification

The predictive scenario-stratification module classified simulated conditions according to combined mechanical and biological inputs. In accordance with the predefined classification framework, lower-risk scenarios corresponded to more favorable healing-index values and lower effective stress burden, whereas higher-risk scenarios reflected reduced healing support and mechanically less favorable fixation conditions. Scenarios characterized by lower stress burden, higher healing support, and moderate load exposure were associated with more favorable healing-index outputs and lower predicted risk scores. Conversely, scenarios involving higher load transfer, reduced healing support, and greater effective implant burden were consistently categorized as higher-risk patterns [20].

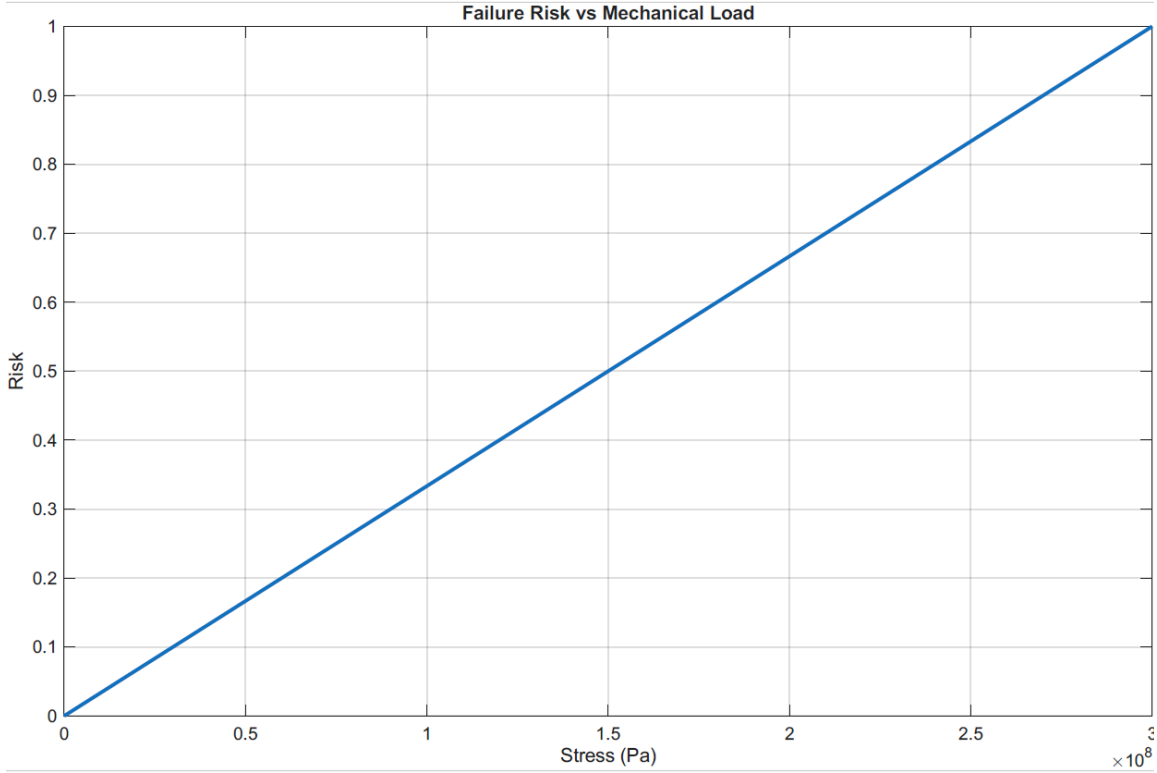


Figure 5. Predicted failure risk as a function of mechanical load.

The predictive scenario-stratification module showed a progressive increase in complication risk with increasing load, supporting load-sensitive classification of simulated fixation conditions.

The modeled relationship between mechanical loading and complication risk is shown in Figure 5, where increasing load corresponded to a progressive rise in predicted failure risk. Under matched healing conditions, CMN-based scenarios generally remained within a lower-risk range than DHS-based scenarios, while stronger healing modulation shifted both constructs toward a more favorable predictive profile.

To further evaluate the discriminative performance of the predictive scenario-stratification module, receiver operating characteristic (ROC) analysis was performed within the simulated classification setting. In this framework, healing values above 0.70 were classified as favorable

healing scenarios, whereas values of 0.70 or below were classified as failure-prone conditions. The resulting ROC curve is presented in Figure 6.

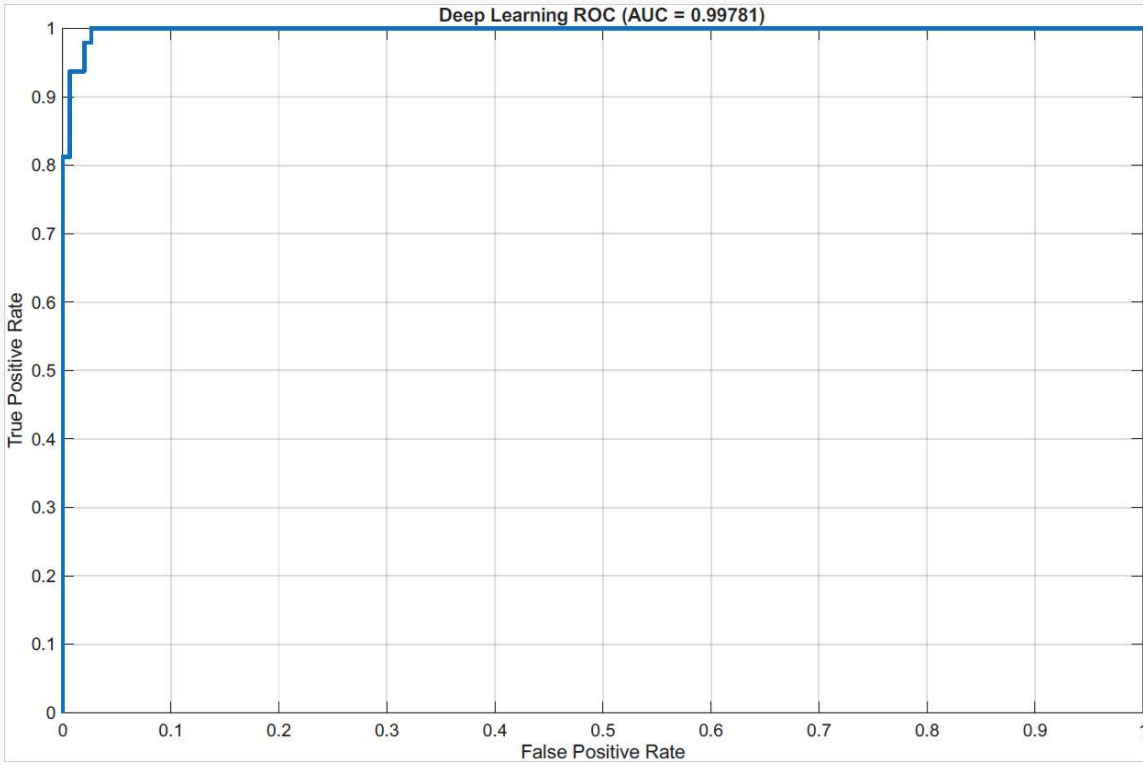


Figure 6. Receiver operating characteristic (ROC) curve of the predictive scenario-stratification module for classification of simulated healing outcomes.

The ROC analysis evaluates the ability of the predictive module to discriminate between favorable healing scenarios and failure-prone fixation conditions within the in silico classification framework. The observed AUC > 0.85 indicates good discriminative performance under the modeled conditions

As shown in Figure 6, the predictive module achieved an AUC > 0.85, indicating good discrimination between favorable healing scenarios and failure-prone fixation conditions under the modeled settings. This result supports the internal consistency of the predictive framework; however, it should be interpreted as model-based performance within a simulated classification setting rather than as externally validated clinical accuracy.

3.5. Sensitivity of the Simulated Outputs

Sensitivity analysis showed that the most influential variables were the load-transfer coefficient, the effective load-bearing area, and the healing sensitivity term, as variation in these parameters produced the largest changes in stress- and risk-related outputs. By contrast, variation in body mass within the tested range produced a more proportional effect on the simulated mechanical response. Importantly, the relative biomechanical advantage of CMN over DHS remained stable across the tested parameter space. Likewise, the directional effect of healing modulation remained consistent, with stronger biological support associated with reduced effective stress and lower risk classification. These findings support the robustness of the framework as a comparative mechanobiological model rather than as a single-condition simulation.

3.6. Integrated Interpretation of the Results

Taken together, the simulation results support three main findings. First, CMN showed a more favorable biomechanical profile than DHS across the modeled intertrochanteric fixation scenarios. Second, peptide-inspired healing modulation improved the simulated biological environment and contributed to reduction in effective implant stress. Third, the predictive scenario-stratification module provided coherent classification of modeled fixation conditions by integrating mechanical and healing-related variables into a single interpretive output. These findings should be interpreted as in silico, hypothesis-generating results derived from a proof-of-concept computational framework. Although they do not represent direct clinical evidence, they provide a coherent basis for future refinement through finite-element benchmarking, experimental calibration, and patient-level validation.

4. Discussion

The present study proposes an in silico mechanobiological framework for comparative evaluation of CMN and DHS osteosynthesis under peptide-inspired healing modulation. Three principal findings emerged from the simulations: (i) CMN showed a more favorable mechanical profile than DHS across the modeled loading scenarios, (ii) stronger healing modulation was associated with lower effective implant burden, and (iii) the predictive scenario-stratification module enabled coherent classification of healing favorability and complication risk. Taken together, these findings support the value of integrating fixation mechanics, biologically inspired healing support, and predictive interpretation within a unified computational framework. This perspective is relevant because current literature on fixation biomechanics, biological augmentation, and predictive orthopedic modeling remains largely fragmented, with limited overlap between these domains [1,2,5,8].

A central observation of the model was that CMN consistently exhibited lower predicted stress values than DHS. This trend is compatible with the established biomechanical rationale for intramedullary fixation, which provides a more central load-transfer pathway and a shorter lever arm than extramedullary constructs [13,14,16]. Meta-analytic evidence suggests that intramedullary fixation may offer mechanical or clinical advantages in selected unstable intertrochanteric fracture settings, although superiority is not consistent across all outcomes [13,14]. Within the present framework, the CMN advantage remained stable across the tested simulation space, indicating that the observed difference was not restricted to a single loading assumption but persisted under multiple modeled conditions.

At the same time, these findings do not imply that DHS is universally inferior. Rather, the simulations suggest that DHS is more sensitive to unfavorable loading and delayed healing conditions, particularly when effective implant stress remains elevated. This interpretation is clinically relevant because fixation success in DHS depends strongly on fracture pattern, reduction quality, implant placement, and local mechanical parameters such as tip–apex distance [3,4,9]. Accordingly, the present framework supports a more nuanced interpretation in which fixation performance depends not only on device category, but also on the interaction between construct mechanics and the evolving biological state of the fracture [3,4].

A second important finding was the favorable effect of peptide-inspired healing modulation on the modeled recovery environment. Stronger healing support was associated with progressive reduction in effective implant stress, suggesting that biologically supported healing may facilitate earlier load sharing between the implant and the healing fracture region. This interpretation is directionally consistent with the regenerative literature indicating that bioactive peptides may support osteogenic signaling, tissue integration, and repair processes during bone healing [5,6,12]. However, the healing term in the present framework was intentionally modeled as a normalized biologically inspired abstraction rather than as a surrogate for a specific therapeutic peptide or a clinically validated dosing scheme. Its purpose

was to improve mechanobiological interpretability at the simulation level, not to predict the efficacy of any single peptide intervention [5,6,12].

The study also highlights the potential usefulness of a predictive scenario-stratification layer within orthopedic modeling. Existing AI applications in hip-fracture care have focused primarily on fracture detection, imaging interpretation, and postoperative outcome prediction from clinical datasets [8,15,17]. By contrast, the present framework uses a predictive module as a decision-support component that translates simulated mechanical and healing conditions into interpretable risk categories. In this sense, the predictive layer does not function as a standalone clinical artificial intelligence system, but rather as a computational bridge between mechanobiological simulation outputs and scenario-based interpretation. The observed discriminative performance within the simulated classification setting supports its internal utility; however, this result should not be interpreted as externally validated clinical performance [8,15].

From a translational perspective, the framework supports the view that future orthopedic planning may benefit from multimodal computational models integrating implant mechanics, biologically informed healing support, and predictive scenario analysis. Such systems could contribute to comparative assessment of fixation strategies not only on the basis of fracture classification or surgeon preference, but also according to expected healing dynamics, loading characteristics, and modeled complication risk. This may be particularly relevant in elderly or biologically vulnerable patients, in whom impaired bone quality and delayed regeneration contribute substantially to fixation-related complications [1,2,8].

Several limitations of the present study should be acknowledged. First, the biomechanical formulation was intentionally simplified and did not include full finite-element representation, anisotropic bone properties, or patient-specific anatomical geometry [7,10,11]. Second, the healing-support term was modeled as a generalized amplification function and was not calibrated to experimental pharmacokinetic or clinical peptide-response datasets [5,6]. Third, the predictive module was scenario-based and was not trained or validated on a real-world prospective patient cohort [8,15]. Therefore, the findings should be interpreted as hypothesis-generating in silico results rather than as validated clinical predictions. These limitations are important, but they do not diminish the value of the framework as a proof-of-concept platform for integrating biomechanics, regenerative modulation, and predictive analysis [7,8].

Future work should proceed in three main directions. First, the biomechanical component should be refined using patient-specific imaging and finite-element benchmarking in order to improve anatomical realism and local stress estimation [7,10,11]. Second, peptide-related parameters should be informed by experimental or preclinical healing datasets, particularly for agents with known osteogenic or angiogenic activity [5,6,12]. Third, the predictive module should be expanded and externally evaluated using patient-level orthopedic datasets that include fixation type, fracture morphology, patient characteristics, healing outcomes, and complication events [8,15,17]. Such developments would support progression from a conceptual comparative framework toward clinically relevant computational decision support.

Overall, the present findings support the central premise of the study: intertrochanteric fracture fixation should not be evaluated solely as a mechanical problem, but as a dynamic interaction between implant stability, healing progression, and predictive risk assessment. Within this integrated perspective, CMN appears mechanically more favorable under the modeled conditions, peptide-inspired healing modulation provides a biologically meaningful mechanism for stress reduction, and predictive scenario stratification offers a pathway toward more individualized interpretation of fixation behavior. These findings highlight the potential of mechanobiological in silico modeling as a foundation for future computational support in orthopedic trauma management.

5. Conclusions

This study presents a comparative in silico mechanobiological model of CMN and DHS osteosynthesis under peptide-inspired healing modulation. The findings indicate that CMN maintained a more favorable biomechanical profile than DHS under the modeled conditions, while healing modulation contributed to progressive reduction in effective implant stress over time. In addition, the predictive scenario-stratification module enabled coherent classification of modeled fixation conditions according to healing favorability and complication risk.

Overall, the proposed model supports the view that intertrochanteric fracture fixation should be approached not only as a structural problem, but also as a dynamic interaction between mechanical stability, healing progression, and predictive risk assessment. Although the model remains conceptual, it provides a strong foundation for future development of advanced computational tools for fracture-fixation analysis and orthopedic decision support.

Acknowledgements: Not applicable.

Author contributions

Ivana Mitrevska

Conceptualization (equal), Visualization (equal), Methodology (equal), Formal analysis (equal), Writing – original draft (equal)

Ivana Mickoski

Data curation (equal), Investigation (equal), Software (equal)

Igor Merzanovski

Conceptualization (equal), Supervision (equal)

Funding: This research received no external funding.

Data Availability Statement: The datasets generated and/or analyzed during the current study areavailable from the corresponding author upon request.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Competing interests: The authors declare no competing interests.

Abbreviations

AI: Artificial Intelligence; CMN: Cephalomedullary Nail; DHS: Dynamic Hip Screw; TAD: Tip–Apex Distance; FEA: Finite Element Analysis; H(t): Time-Dependent Healing Function; P(t): Peptide Activity Function; σ: Mechanical Stress; σ_eff: Effective Mechanical Stress; F: Applied Force; A: Load-Bearing Area; m: Body Mass; g: Gravitational Acceleration; α: Load Distribution Coefficient; BMP: Bone Morphogenetic Protein; IGF-1: Insulin-Like Growth Fac-tor 1; BPC-157: Body Protection Compound 157

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