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Comparison of Titanium, Magnesium, and Polymer-based Cortical Screw Fixation for Fulkerson Tibial Tubercle Osteotomy: A Finite Element Analysis

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ABSTRACT

Objective: To compare the biomechanical performance of titanium alloy (Titanium-Aluminum-Vanadium Alloy, Ti-6Al-4V), magnesium alloy (Magnesium-Yttrium-Rare Earth-Zirconium, MgYREZr), and polylactide (PLA) cortical screws in the fixation of Fulkerson tibial tubercle osteotomy (TTO) using finite element analysis (FEA).

Materials and Methods: A three-dimensional tibial model was created from computed tomography data of a 20-year-old male patient and simulated with a standardized Fulkerson osteotomy fixed using two bicortical screws. The screws were modeled using three different biomaterials. FEA simulations were performed under two loading conditions: 390 N (physiological gait) and 1654 N (worst-case scenario). Stress distribution (von Mises) and displacement were recorded for the osteotomy construct and screws.

Results: Under 390 N loading, Ti-6Al-4V screws demonstrated the highest mechanical resistance (max. stress: 123,830 MPa; displacement: 0.084 mm), followed by MgYREZr (95,172 MPa; 0.098 mm) and PLA (81,939 MPa; 0.219 mm). Under 1654 N loading, Ti-6Al-4V screws again showed superior performance (669,880 MPa; 0.333 mm), whereas MgYREZr (745,470 MPa; 0.407 mm) and PLA (339,720 MPa; 0.882 mm) showed increased stress and deformation, with PLA screws exhibiting the least mechanical stability.

Conclusion: Titanium screws demonstrated the highest mechanical reliability across both loading conditions, supporting their continued use in TTO, particularly in high-demand clinical scenarios. Although biodegradable materials, such as MgYREZr and PLA, offer theoretical advantages by eliminating the need for implant removal, their biomechanical performance remains inferior to titanium screws.

Keywords: Finite element analysis, Fulkerson osteotomy, Magnesium screw, Patellar instability, Polymer screw, Tibial tubercle osteotomy, Titanium screw

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INTRODUCTION

Anteromedialization of the tibial tubercle (TT), commonly referred to as the Fulkerson osteotomy (FO), is a well-established surgical technique for the management of recurrent patellofemoral instability (PFI), particularly in patients exhibiting increased lateralization of the TT.[1,2] It is evident that reducing the quadriceps (Q) angle and improving patellar tracking within the trochlear groove (TG) effectively enhances joint biomechanics and patellofemoral congruity.[3] A key indication for FO is an elevated TT–TG distance, typically assessed through axial imaging modalities, such as computed tomography (CT).[4,5]

One of the major advantages of this technique is its ability to achieve simultaneous anteriorization and medialization of the TT, thereby allowing precise correction of patellar alignment and, when necessary, adjustment of patellar height. Despite these benefits, the procedure is associated with several potential complications, including tibial fracture, nonunion, infection, limited post-operative range of motion, and implant-related irritation.[6,7] Fixation is traditionally accomplished using metallic cortical screws, generally two or three, which provide compression and stability during the healing process.[4] However, the limited soft tissue coverage over the TT often leads to hardware prominence and discomfort, particularly during kneeling. Such symptoms are a common reason for secondary implant removal, reported in a significant proportion of patients undergoing this procedure.[5,8] Some authors have even advocated for routine screw removal regardless of the presence of symptoms, although this approach increases healthcare costs and exposes patients to additional surgical risks.[8]

Bioabsorbable fixation systems have been investigated as alternatives to permanent metallic implants to address these issues. These materials gradually degrade and are replaced by native tissue, potentially eliminating the need for implant removal and avoiding complications, such as metal ion release and stress shielding.[9–11] Magnesium alloys (Magnesium-Yttrium-Rare Earth-Zirconium, MgYREZr) and polymer-based materials have attracted particular attention due to their favorable biocompatibility and resorption characteristics among bioabsorbable options. Nonetheless, concerns remain regarding their mechanical integrity, especially in high-load environments, such as the extensor mechanism of the knee. Since the fixation construct must withstand substantial forces during the early post-operative period to allow safe mobilization and progressive weight-bearing, ensuring sufficient mechanical strength is critical for successful osteotomy healing.

Although the use of bioabsorbable screws is becoming more prevalent in various orthopedic applications, evidence regarding their performance in TT osteotomy (TTO) remains limited. While previous studies have assessed the mechanical performance of various screw materials in orthopedic applications, none has directly compared titanium, magnesium, and polymer-based screws in the specific context of Fulkerson TTO using finite element modeling. The present study aims to address this gap by utilizing finite element modeling (FEM) to evaluate and compare the mechanical performance of these three screw types under simulated physiological loading conditions. This study uniquely provides a standardized finite element modeling approach to directly compare titanium, magnesium, and polymer-based screw fixation in TTO, allowing for objective assessment of their mechanical performance under both physiological and extreme loading conditions. We hypothesize that although biodegradable materials may offer clinical advantages by eliminating the need for hardware removal, their mechanical properties could be inferior to those of titanium screws, potentially limiting their effectiveness in high-demand fixation scenarios, such as TT osteotomies.

MATERIALS AND METHODS

Study Design

This study employed the finite element method (FEM) to investigate the behavior of screws composed of three distinct biomaterials when utilized to secure a FO under linear static loading conditions. The study pre-supposed that the materials used were homogeneous and isotropic, and it postulated that they would exhibit linear elastic behavior. Furthermore, the interactions among the various components within the model were regarded as non-linear. Within a standard FO model, screws manufactured from three materials (titanium, magnesium, and polymer) underwent testing under two distinct loading conditions. Ethical approval was not required because this finite element analysis (FEA) study was conducted virtually and involved no human or animal subjects.

Modeling of the FO

To create a realistic tibial model, we utilized a computerized tomography (CT) examination of a 20-year-old male with recurrent PFI. This individual had a height of 174 cm and weighed 76 kg. Notably, the patient exhibited excessive lateralization of the TT, with a TT-TG distance of 23 mm, indicating a potential need for a FO. The CT examination was conducted using a CT scanner (Siemens go. up, Siemens, Munich, Germany) at our university hospital. The specific scan parameters consisted of 232 axial slices captured at 120 kV, 30 mA, with a slice distance of 1.0 mm and a field of view spanning 218 mm, extending from the supracondylar femur to the proximal tibia. For modeling and simulating the FEA scenarios, we employed various software tools, including Materialise Mimics–Medical three-dimensional (3D) image-based engineering software (Materialise NV, Belgium), SolidWorks parametric solid modeling software (Dassault Systems SolidWorks Corp, Waltham, USA), and Analysis System Software (FEA software) (ANSYS) Workbench FEA code (ANSYS, Ltd., Canonsburg, PA, USA).

The FO model was created based on previous descriptions.[12] The osteotomy length was 72 mm, and the osteotomy plane was angled at 45° to the posterior condylar axis of the tibia. Both the upper and lower planes of the osteotomy were sloped. The fragment was shifted 10 mm toward the medial side. There was no gap between the fragments at the osteotomy plane. The model was secured using two 4.5 mm screws that were inserted parallel to each other in the sagittal plane and perpendicular to the posterior cortex of the tibia, as suggested in earlier studies. A bicortical fixation was performed (Fig. 1). Screws made of three different materials were used on the same model. The first screw model was made of titanium alloy (Titanium-Aluminum-Vanadium Alloy, Ti-6Al-4V), the second was a MgYREZr, and the third was polylactide (PLA) screws. The characteristics of the cortical screw (International Organization for Standardization/TC 150/SC 5, 1991) were as follows: A thread diameter of 4.5 mm, a thread pitch of 1.75 mm, a shaft diameter of 3.0 mm, and a head diameter of 8.0 mm. The upper screw was 48 mm in length, and the lower screw was 36 mm in length.

Boundary Conditions and Material Properties

The models were loaded with two different intensities of force. The first aimed to imitate ordinary walking, and the other aimed to imitate load to failure, which is the worst-case scenario. In previous studies, the typical maximal quadriceps force applied to the TT during the extension phase of the knee during walking is between 350 and 390 N. Davis et al.[13] found that a TTO failure load fixed with two 4.5 mm cortical screws was 1654 N in a biomechanical study performed on fresh frozen cadavers. Thus, 390 N and 1654 N traction forces were applied to the patellar tendon footprint at the TT to each model, respectively (Fig. 2).

The proximal tibia was supported at the medial and lateral condyles, while the distal tibia was attached to the ground in an anatomical position. The force was applied to the patellar tendon footprint on the TT with a vectorial angle corresponding to the orientation of the patellar tendon fibers, which were analyzed and extracted from the CT data using the rendering technique. The 3D model specified the frictional contact (non-linear contact) between the screw-bone and bony fragment surfaces. In addition, bonded contact definitions were created between the cortical and trabecular bone. The screws were pre-loaded with 50 N, and prior studies found that the friction coefficients between bone and screw were 0.46 and 0.37, respectively (Table 1).[14–18] The material characteristics

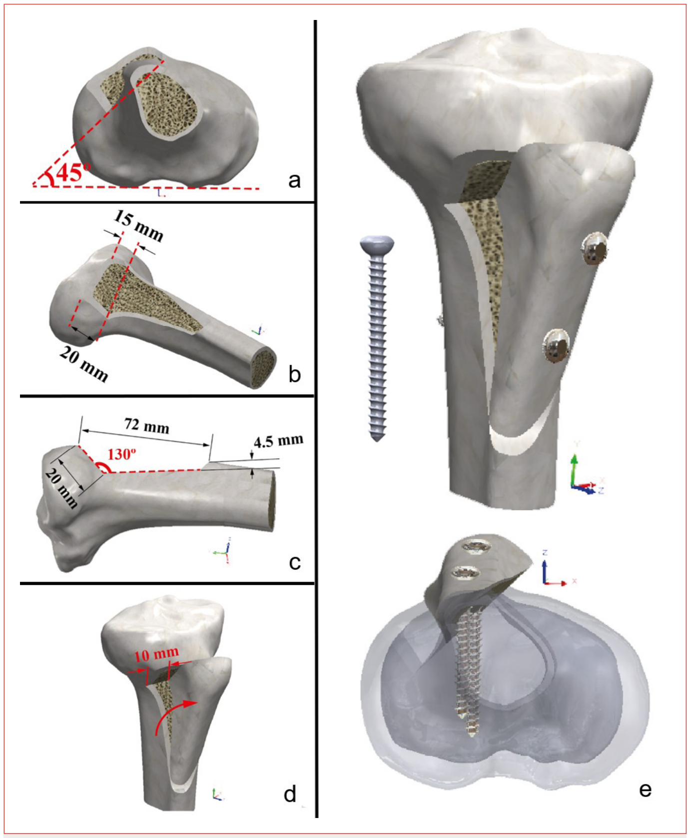
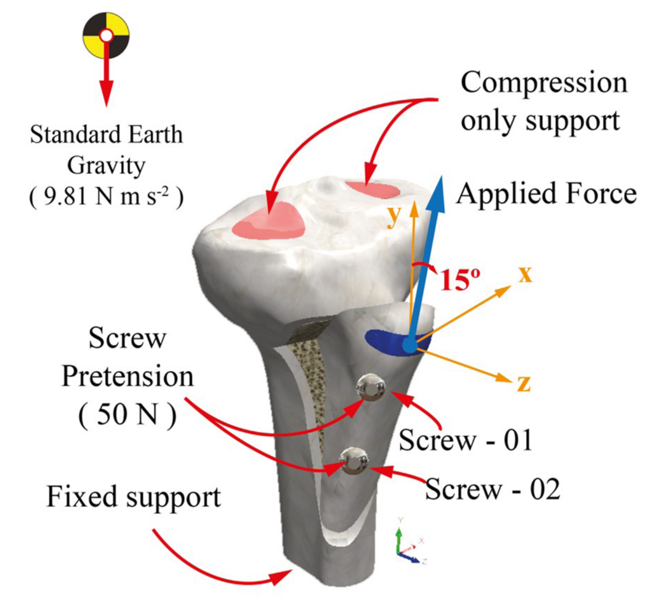


Figure 1. Three-dimensional finite element modeling of the Fulkerson tibial tubercle osteotomy. **(a)** Axial view showing the 45° osteotomy angle relative to the posterior condylar axis of the proximal tibia. **(b)** Sagittal view demonstrating the osteotomy dimensions: 15 mm anteriorization and 20 mm medialization. **(c)** Lateral view illustrating the osteotomy length (72 mm), cortical screw diameter (4.5 mm), and insertion angle (130° between screws). **(d)** Anteroposterior view showing the 10 mm medial translation of the osteotomized fragment. **(e)** Three-dimensional rendering of the final osteotomy model with two parallel bicortical screws inserted perpendicular to the posterior tibial cortex, used to simulate fixation with three different materials (titanium, magnesium alloy, and polymer).

for cortical and trabecular bone and the screws were allocated independently under the assumptions of the isotropic homogeneous linear elastic material model (Table 2).[19–29]

Verification of Mesh Structure and Quality of the Models

The quality of a model's mesh structure has a significant impact on the accuracy of FEA simulations. One of the most important quality indicators for a mesh structure is the skewness metric, which indicates how closely a face or cell resembles an ideal one in a finite element model. The skewness values showed



Applied Force	Ti-6Al-4V Screw	MgYREZr Screw	PLA Screw
390 N	Scenario 1	Scenario 3	Scenario 5
1654 N	Scenario 2	Scenario 4	Scenario 6

Figure 2. Boundary conditions and loading scenarios for finite element analysis. The tibial model was fixed distally and supported proximally to allow compression only. A 15° vectorial force simulating patellar tendon traction was applied to the tibial tubercle, with 50 N pretensions on both screws. Six simulation scenarios were created by combining two loading conditions (390 N and 1654 N) with three screw materials: Titanium alloy, magnesium alloy, and polylactide.

Table 1. Coefficients of friction and screw fixation pre-load assigned in the FEA setup

Coefficient of friction between	Bony parts and fixation screw	0.37
	Bony parts	0.46
Screw fixation pre-load (N)	50	

excellent mesh quality (average: 0.263) in all analyzed scenarios. The solid models' final mesh structure was produced using a curvature-based meshing technique. An average of 1.4 million components and 2.1 million nodes were found for all solid models. A visual illustration of the models' meshing is shown in Figure 3. Each simulation scenario was independently run with the same boundary conditions, and the resulting visual and numerical outputs were then recorded.

Assessment of Simulation Results

Calculations were made to determine the total deformation of the osteotomized fragment. The equivalent (von Mises) stress and total deformation distributions on the components were obtained using the simulation results.

RESULTS

All models have shown a similar displacement behavior. Loading of the models with patellar tendon traction force caused upward migration of the osteotomized TT fragment. Since the upper plane of the osteotomy was sloped, the TT fragment rested on the upper tibial surface. At this point, the top surface of the osteotomy fragment functioned as a fulcrum, and the distal portion of the TT fragment then started to separate from the tibia while the screws were resisting displacement. However, the screws underwent plastic deformation on the level of the lower plane of the osteotomy.

The finite element study compared the biomechanical performance of Ti-6Al-4V, MgYREZr, and PLA screws in the fixation of TTO under two loading conditions, 390 N and 1654 N. Under a

Table 2. Material properties assigned to the FEA model

Parameters	Unit	Model components				
		Cortical bone	Trabecular bone	Ti screws (Ti-6Al-4V)	Mg screw (MgYREZr)	Polymer screws (PLA)
Modulus of elasticity	(MPa)	19100	1000.61	115000	45000	3500
Poisson's ratio	(-)	0.30	0.30	0.33	0.29	0.36
Density	(kg m-3)	1980	830	4500	1840	1250

Ti-6Al-4V: Titanium alloy (Titanium-Aluminum-Vanadium Alloy); MgYREZr: Magnesium alloy (Magnesium-Yttrium-Rare Earth-Zirconium); PLA: Polylactide, FEA: Finite element analysis.

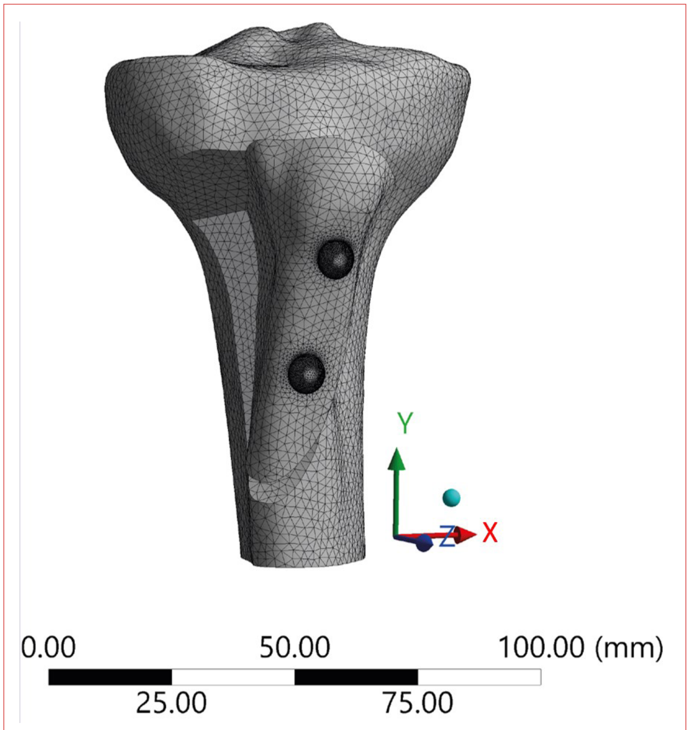


Figure 3. Mesh structure of the tibial tubercle osteotomy model. Curvature-based meshing generated a high-quality finite element mesh with excellent skewness metrics. The model includes approximately 1.4 million elements and 2.1 million nodes.

390 N loading, Ti-6Al-4V screws demonstrated the highest stress resistance, with a maximum equivalent stress of 123,830 Megapascal (MPa) in the screws and a resultant displacement of 0.084 mm in the entire model. MgYREZr screws exhibited a maximum stress of 95,172 MPa and a displacement of 0.098 mm, indicating less resistance compared to Ti-6Al-4V. PLA screws exhibited the lowest stress resistance, with a maximum stress of 81,939 MPa and the highest displacement of 0.219 mm, indicating that they may be the least suitable for high-load applications. Under 1654 N loading, Ti-6Al-4V screws still exhibited the highest stress resistance, with a maximum stress of 669,880 MPa and a displacement of 0.333 mm. MgYREZr screws had a max stress of 745,470 MPa and a displacement of 0.407 mm. PLA screws had a max stress of 339,720 MPa and the largest displacement of 0.882 mm. The data are presented in Table 3.

The visual outputs illustrate that all materials showed increased stress and displacement under higher loading, but the magnitude of change varied significantly across materials. Ti-6Al-4V screws remained the most robust, while PLA screws exhibited the greatest deformation, which may limit their clinical application in high-load-bearing situations (Figs 4 and 5).

DISCUSSION

This FEA revealed a distinct biomechanical stratification among titanium, magnesium, and polymer-based cortical screws utilized for fixation in Fulkerson TTO. Under moderate loading conditions (390 N), reflecting forces typically encountered during normal gait, titanium (Ti-6Al-4V) screws demonstrated superior mechanical behavior, characterized by minimal displacement and high stress resistance. This performance is likely attributable to the high yield strength and fatigue resistance of Ti-6Al-4V, which ensure reliable fixation during daily activities. The differences between materials became more pronounced under higher loading conditions (1654 N), simulating worst-case clinical scenarios, such as accidental falls or sudden high-impact events. While titanium screws maintained structural integrity across both loading conditions, MgYREZr screws exhibited intermediate mechanical performance, with greater deformation likely due to their lower elastic modulus. Polymer-based (PLA) screws, despite their favorable biocompatibility and biodegradability, showed the greatest displacement and lowest stress resistance, raising concerns about their suitability in settings requiring high mechanical stability. Interestingly, while titanium exhibited the highest stress resistance under physiological loading, magnesium showed higher peak stress under high-load conditions. This inversion likely reflects the distinct deformation behaviors and stress concentration points inherent to each material under increasing load, underscoring the non-linear response of MgYREZr in high-stress environments. These findings highlight the delicate balance between mechanical strength and biodegradability in implant selection, underscoring the continued use of titanium screws as the standard of care in patients with high functional demands following TTO.

These results are further supported by previous experimental and computational studies that have evaluated the mechanical performance of various implant materials in osteotomy fixation. In an in vitro biomechanical study, Partio et al.[30] compared bioabsorbable and titanium screws for first tarsometatarsal joint arthrodesis and reported significantly higher yield and maximum failure loads for titanium screws, consistent with our findings that highlight the superior mechanical properties of titanium-based fixation systems. Despite demonstrating lower mechanical strength, the bioabsorbable screws were considered clinically sufficient in selected cases with lower mechanical demands, reflecting a similar trade-off observed in our analysis between strength and degradability. Complementary to these experimental results, Lee et al.[31] utilized finite element modeling to compare titanium, MgYREZr, and polymer-based screws in sagittal split ramus osteotomy, concluding that titanium screws exhibited the highest stress resistance, while magnesium screws offered intermediate

Table 3. The finite element analysis outputs for stress distribution and displacement under two loading conditions (390 N and 1654 N)

Material	FEA outputs	Applied force: 390 N						
		Whole model	Proximal tibial fragment		Tibial tubercle fragment		Screws	
			Cortical	Trabecular	Cortical	Trabecular	Upper screw	Lower screw
Ti-6Al-4V	Max. eq. stress (MPa)	123,830	24,663	25,961	37,097	19,196	123,830	90,358
	Resultant displacement (mm)	0.084	-	-	-	-	0.067	0.054
MgYREZr	Max. eq. stress (MPa)	95,172	25,044	32,486	100,00	30,260	95,172	87,386
	Resultant displacement (mm)	0.098	-	-	-	-	0.082	0.064
PLA	Max. eq. stress (MPa)	81,939	23,114	74,473	56,138	60,778	81,939	59,977
	Resultant displacement (mm)	0.219	-	-	-	-	0.179	0.137
Material	**FEA outputs**	**Applied force: 1654 N**						
		Whole Model	Proximal tibial fragment		Tibial tubercle fragment		Screws	
			Cortical	Trabecular	Cortical	Trabecular	Upper screw	Lower screw
Ti-6Al-4V	Max. eq. stress (MPa)	669,880	102,860	149,290	124,550	104,600	669,880	539,520
	Resultant displacement (mm)	0,333	-	-	-	-	0.269	0.215
MgYREZr	Max. eq. stress (MPa)	745,470	101,350	186,510	158,180	162,360	745,470	353,970
	Resultant displacement (mm)	0.407	-	-	-	-	0.328	0.258
PLA	Max. eq. stress (MPa)	339,720	92,406	339,720	212,700	325,140	339,140	304,870
	Resultant displacement (mm)	0.882	-	-	-	-	0.728	0.562

Ti-6Al-4V: Titanium alloy (Titanium-Aluminum-Vanadium Alloy), MgYREZr: Magnesium alloy (Magnesium-Yttrium-Rare Earth-Zirconium), PLA: Polylactide, FEA: Finite element analysis.

stability superior to polymer screws. Their simulation results, which show minimal deformation of magnesium screws under functional loads and highlight the mechanical inferiority of polymer screws, align closely with the stratified performance outcomes identified in our study. Moreover, the work of Manninen et al.[32] on PLA screw fixation in a high-strain olecranon osteotomy model demonstrated an increased failure rate for absorbable implants under high mechanical loads, reinforcing the observation that polymer-based fixation may not be suitable for load-bearing applications requiring substantial biomechanical stability. Together, these studies corroborate our FEA outcomes and strengthen the conclusion that titanium remains the most mechanically reliable material for TTO fixation. At the same time, biodegradable options, such as magnesium and polymer-based screws, require further optimization to meet the mechanical demands of high-stress clinical scenarios. Another important consideration is that bioabsorbable materials lose their mechanical strength gradually after implantation. This progressive degradation poses a heightened risk of fixation failure, particularly in cases of delayed bone healing. In contrast, titanium screws maintain their initial biomechanical integrity over time, offering consistent mechanical support throughout the healing process.

To date, the available literature on the use of bioabsorbable screws in TTO remains limited, with only two clinical studies evaluating magnesium-based implants and a single cadaveric biomechanical study addressing PLA screws. Specifically, Ünal et al.[8] and Delsmann et al.[33] reported favorable clinical outcomes using magnesium screws for TT fixation, with successful union and no fixation failures observed during follow-up. However, in both studies, patients were managed with strict non-weight-bearing protocols for the first 6 weeks post-operatively, followed by gradual load progression. This suggests that reduced mechanical stress during the early healing phase may have contributed significantly to these positive outcomes. This approach contrasts with the me-

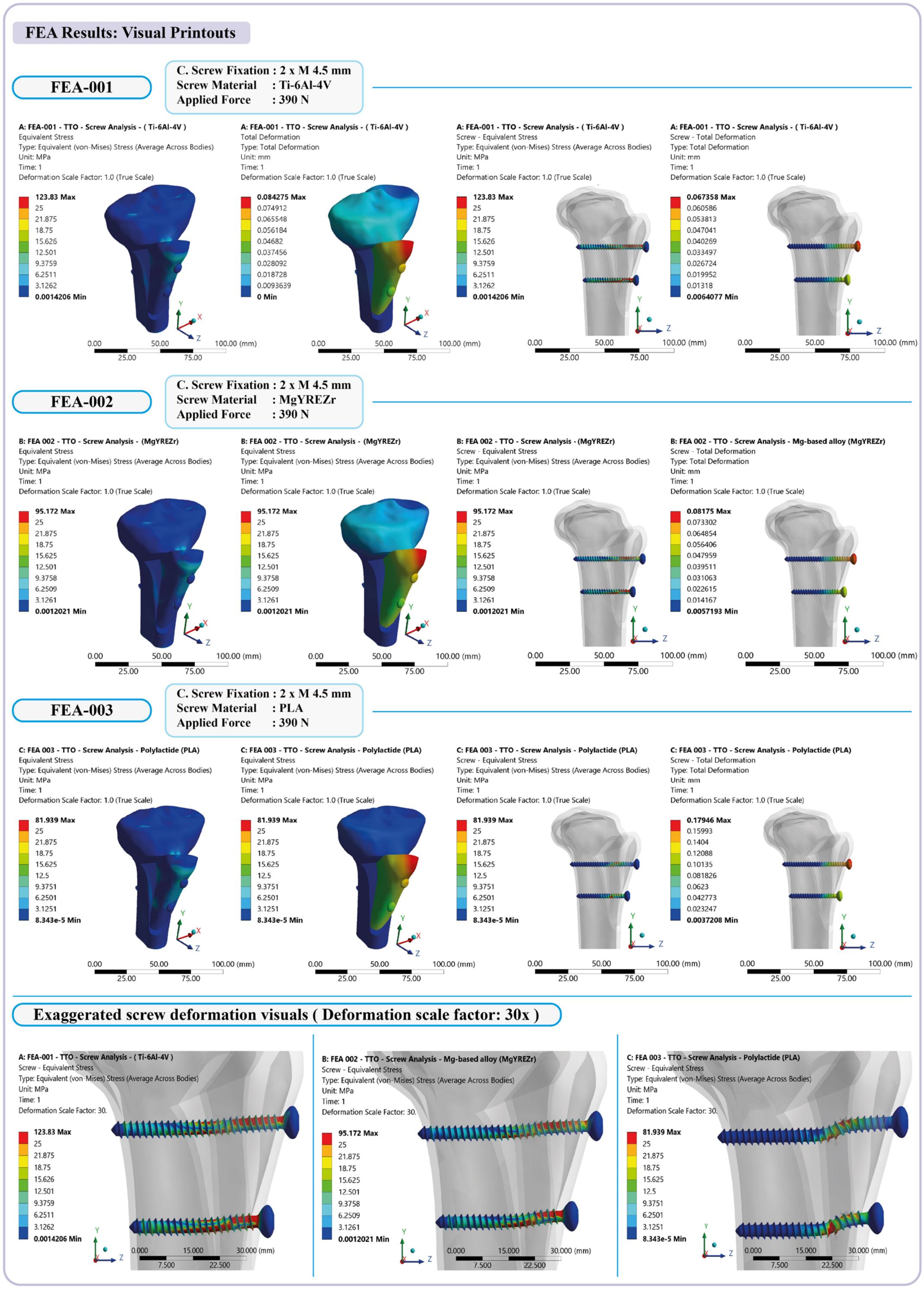


Figure 4. Finite element analysis results under physiological load (390 N). Stress distribution and deformation outputs for titanium alloy, magnesium alloy, and polylactide screws. The upper row shows von Mises stress, total deformation, and screw deformation (true scale), while the lower row presents screw deformation exaggerated 30× to visualize bending and displacement differences across materials

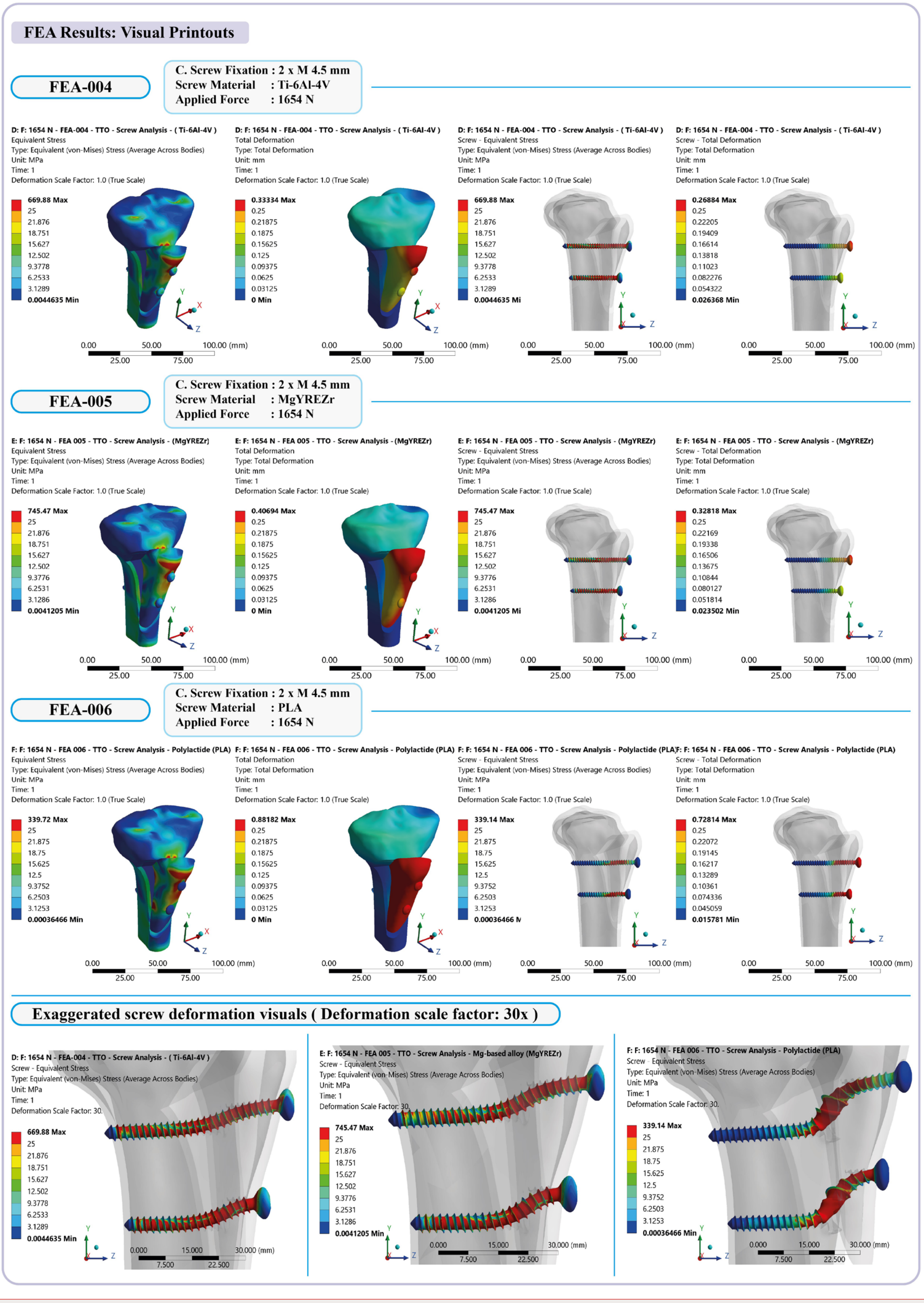


Figure 5. Finite element analysis results under high-load conditions (1654 N). Visual comparison of stress and deformation patterns for all three screw types under worst-case loading. As in Figure 4, top panels show actual stress and displacement fields, while bottom panels depict screw deformation at a 30× scale to highlight material behavior under elevated force.

chanical performance of titanium screws, which allow for earlier mobilization and weight-bearing due to their superior fixation strength. In addition to these clinical studies on magnesium, Nurmi et al.[34] conducted the only biomechanical study on PLA screws in TT transfer, utilizing a cadaveric model without biological healing, where fixation strength was significantly lower for PLA screws compared to metallic screws (566 N vs. 984 N, respectively). It is essential to note that Nurmi et al.'s [34] experimental design employed static loading in a single-screw configuration without proximal step-cut support, which limits the applicability of their findings to clinical practice, where two-screw fixation and dynamic biological processes are crucial. In contrast, the finite element modeling employed in the present study simulated both physiological loading and worst-case high-load scenarios, offering a more comprehensive assessment of implant behavior under varied mechanical demands. To the best of our knowledge, this study represents the first FEA evaluating bioabsorbable screw fixation in Fulkerson TTO, thereby filling a notable gap in the present literature. Given their reduced mechanical resistance, magnesium and polymer screws may be suitable for select patient populations, such as adolescents or individuals with low physical demands, or in scenarios that permit prolonged non-weight-bearing or partial weight-bearing rehabilitation protocols.

A key strength of this study is its standardized FEA-based methodology, which allows for a direct comparison of different biomaterials under consistent loading conditions. However, certain limitations should be acknowledged. As a computational model, the study does not replicate biological healing, bone remodeling, or soft tissue contributions, which are known to influence fixation stability in vivo. In addition, the assumption of isotropic, homogeneous, and linear elastic behavior for all materials, particularly for polymer-based materials, such as PLA, does not fully represent their real-world mechanical response. Moreover, the absence of cyclic or fatigue loading simulations limits the extrapolation of these results to long-term clinical behavior, particularly in scenarios where repetitive micro-loading could compromise fixation. Furthermore, although the direction of the patellar tendon force was derived from anatomical CT reconstruction, it was assumed to remain constant; however, in reality, this vector may vary with knee flexion angle, introducing additional clinical variability. Finally, although fixation with three screws is commonly used in clinical practice, only a two-screw model was analyzed in this study, limiting the exploration of potential reinforcement effects from additional screw fixation. Despite these limitations, the findings offer valuable biomechanical insight to support implant selection in TTO fixation.

CONCLUSION

This FEA demonstrated that titanium screws provide superior mechanical stability compared to magnesium alloy and polymer-based screws for TTO fixation. Although bioabsorbable screws offer the advantage of eliminating the need for secondary implant removal, their mechanical resistance remains inferior to that of titanium, particularly under high-load conditions where implant stability is crucial to prevent fixation failure. Although headless screw designs may help reduce implant-related symptoms and avoid hardware removal, this recommendation remains speculative, as such configurations were not included in the present FEA model. These findings support the continued use of titanium screws as the most reliable fixation option in scenarios where early weight-bearing and mechanical robustness are required, and highlight the need for future research to improve the performance of bioabsorbable implants for broader clinical applicability in TTO.

DECLARATIONS

Ethics Committee Approval: Ethical approval was not required because this finite element analysis (FEA) study was conducted virtually and involved no human or animal subjects.

Conflict of Interest: The authors declare that there is no conflict of interest.

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