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Original Research Article

Equation-of-state inspired theoretical modeling of biomedical materials: Analogies with Neutron Star Matter

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ABSTRACT

We present a theoretical framework that adapts the equation-of-state (EOS) formalism of neutron star physics to the mechanical modeling of biomedical materials. By reinterpreting pressure density relations as effective stress–density constitutive laws, we construct polytropic EOS analogues applicable to both soft biological tissues and hard biomaterials such as bone and bio-ceramics. The EOS parameters are mapped to physically meaningful quantities representing material rigidity and nonlinear microstructural response. Stability conditions inspired by compact-star theory are translated into mechanical admissibility criteria, ensuring positive incremental stiffness. Numerical simulations over a wide range of normalized densities demonstrate clear differentiation between soft and stiff biological matter, as well as sensitivity to EOS parameters. The framework is further extended to piecewise EOS models, enabling the representation of damage, densification, and phase-transition like behavior in biological materials. Although phenomenological in nature, the proposed framework provides a unified physics-inspired language for tissue characterization, biomaterial design, and theoretical failure analysis. The model is fully analytical, scalable, and readily extensible to thermal, viscoelastic, and anisotropic effects, establishing a novel inter disciplinary bridge between nuclear astrophysics and biomedical material science.

1. Introduction

The physics of compact stars relies fundamentally on the equation of state (EOS), which governs the relationship between pressure and density in ultra-dense matter [1-4]. In neutron star interiors, the EOS determines macroscopic observables such as mass, radius, and stability. In parallel, biomedical materials such as soft tissues and mineralized bone exhibit complex nonlinear stress–strain behavior governed by their internal microstructure and composition [5-8]. The objective of this work is to develop an EOS inspired theoretical framework for biomedical materials by adapting the polytropic EOS formalism commonly used in neutron star physics, and to analyze the resulting stress–density relations through numerical simulations. Despite the enormous difference in physical scales, both systems share a common theoretical challenge: describing how internal stresses arise from the collective behavior of dense and heterogeneous matter. In this work, we explore the possibility of translating this EOS formalism into a biomechanical context by reinterpreting pressure–density relations as effective stress–density constitutive laws for biomedical materials. Within this framework, the polytropic EOS widely used in compact-star physics is mapped onto an analytical constitutive model capable of describing nonlinear stiffening behavior in both soft biological tissues and hard biomaterials. The present study therefore aims to establish a conceptual and mathematical bridge between dense-matter astrophysics and biomedical material science. By introducing EOS-inspired constitutive relations and stability conditions, we demonstrate that key mechanical characteristics of biological

materials can be captured using a compact set of parameters analogous to those governing neutron star matter. This interdisciplinary approach provides a unified physics-based language for describing nonlinear material response and may offer new insights for tissue characterization, biomaterial design, and theoretical modeling of mechanical failure. Although the present work focuses on biomedical materials, the conceptual framework is inspired by EOS modeling developed for compact-star physics. The detection of gravitational waves from the binary neutron star merger GW170817 has provided strong constraints on the properties of dense matter and neutron star structure [9-10]. In addition, recent X-ray observations from the NICER mission have provided precise measurements of neutron star masses and radii, offering further constraints on the equation of state of dense matter [11-12]. This work therefore explores how concepts originally developed for compact object can be reformulated to provide a compact analytical framework for describing nonlinear mechanical behavior in biomedical material.

2. Equation-of-state formalism

In neutron star modeling, the EOS is defined as:

$$P = P(\rho), \quad (1)$$

where P is pressure and ρ is normalized density. A widely used parametrization is the polytropic EOS,



$$P = K\rho^\gamma, \quad (2)$$

which has been extensively used in neutron star structure modeling [3,13,14], where K is a stiffness constant and γ is the polytropic index encoding microphysical interactions. A review of neutron star structure and dense matter EOS can be found in recent works on compact object modeling [15].

3. Classification of biomedical materials

3.1 Soft biological matter

Soft biological tissues such as cartilage, tumors, and brain matter exhibit compliant mechanical behavior with relatively low resistance to deformation and weak nonlinear stiffening under compression [5, 6]. Although many such tissues are nearly incompressible in the strict volumetric sense using a soft polytropic (EOS) with $K \ll 1$, $1 < \gamma \lesssim 1.5$.

3.2 Hard biological matter

Hard biological materials such as bone, dental tissue, and bio-ceramics exhibit strong nonlinear stiffening, high resistance to deformation, and fracture toughness [8, 16]. These materials can be described by a stiff polytropic EOS with $K \gg 1$, $1.8 \lesssim \gamma \lesssim 3$.

4. Theoretical foundations of equation-of-state modeling

4.1 Equation of state in compact-Star physics

In compact-star physics, The EOS governs the macroscopic properties of neutron stars, including their mass–radius relation, stability limits, and response to perturbations. Phenomenological EOS models are frequently employed as introduced in Equation (2) widely used in neutron star modeling.

4.2 Energy density and variational interpretation

In relativistic stellar structure theory, Pressure may be derived from energy density through the thermodynamic relation [17] as follows:

$$P = \rho^2 \frac{d}{d\rho} \left(\frac{\epsilon}{\rho} \right). \quad (3)$$

This expression highlights that pressure arises as a response to changes in density, emphasizing the energetic origin of mechanical resistance. This energetic viewpoint motivates the reinterpretation of stress in condensed matter systems as an effective derivative of an internal material energy density. Such a perspective provides a natural bridge between EOS theory and continuum mechanics, enabling astrophysical stability conditions into mechanical admissibility criteria. This criterion plays a central role in the present framework, as it directly translates into a condition of positive incremental stiffness in biomedical materials.

4.3 Stability condition

Mechanical stability in compact-star matter requires positive compressibility [18] as expressed below, violation of which condition signals mechanical instability.

$$\frac{dP}{d\rho} > 0. \quad (4)$$

5. EOS-inspired constitutive modeling of biomedical materials

5.1 Mapping of physical variables

To adapt the EOS formalism to biomedical materials, mapping between astrophysical and biomechanical variables is introduced as shown in Figure 1.

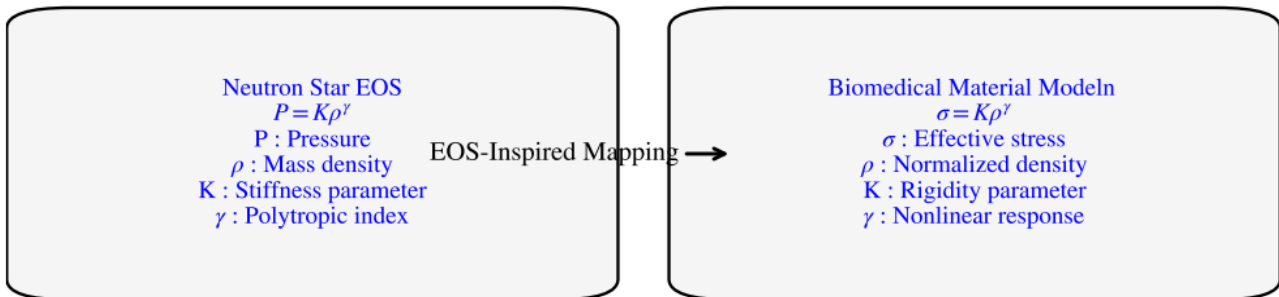


Figure 1: Conceptual mapping between the equation-of-state formalism used in neutron star physics and the EOS-inspired constitutive model proposed for biomedical materials. Astrophysical variables such as pressure and density are reinterpreted as effective stress and normalized material density, while the parameters K and γ correspond to material rigidity and nonlinear microstructural response.

The effective biomedical EOS is therefore written as:

$$\sigma = K\rho^\gamma. \quad (5)$$

For biomedical materials positive incremental elastic modulus and stability condition yields,

$$\frac{d\sigma}{d\rho} = K\gamma\rho^{\gamma-1} > 0. \quad (6)$$

5.2 Physical interpretation of EOS parameters

The parameter K governs the overall stiffness scale of the material and is influenced by microstructural connectivity, collagen density, or mineralization. Larger values of K correspond to harder biological materials such as bone or bio-

ceramics, while smaller values are associated with soft tissues. The mass density ρ is mapped to a normalized material density capturing effects such as porosity, hydration, and mineral content. The polytropic index γ controls the degree of nonlinearity in the stress–density response. Values of γ close to unity correspond to weakly nonlinear materials and larger values indicate strong strain stiffening and resistance to densification.

5.3 Relation to classical constitutive models

Many conventional biomechanical models employ power-law or exponential stress–strain relations. The EOS-inspired formulation may be viewed as a density-based analogue of

these models, offering a compact description with explicit stability constraints. Unlike purely phenomenological approaches, EOS framework naturally incorporates admissibility conditions inherited from dense-matter physics. Classical biomechanical descriptions often employ hyperelastic or exponential stress–strain models [5, 7, 19].

6. Numerical simulations and results

6.1 Simulation setup

Numerical simulations were conducted to explore the qualitative behavior of EOS-inspired laws across a range of material parameters. The density was varied within the interval $\rho \in [0.1, 5)$, covering from highly porous to densely packed biological matter. Numerical parameter exploration has

become a standard tool in astrophysical EOS modeling and stability analysis [20]. Three EOS parameters are selected here to model soft biological tissues and hard biomaterials.

6.2 Representative EOS models

For soft biological tissues, the EOS was chosen as:

$$\sigma_{\text{soft}} = 0.5\rho^{1.3}, \quad (7)$$

while for hard biomaterials such as bone or bio-ceramics, the EOS was taken respectively as:

$$\begin{aligned} \sigma_{\text{bone}} &= 1.5\rho^{1.8}, \text{ and} \\ \sigma_{\text{bone}} &= 1.5\rho^{1.8}, \text{ and} \\ \sigma_{\text{bio-ceramic}} &= 3.0\rho^{2.5}. \end{aligned} \quad (8)$$

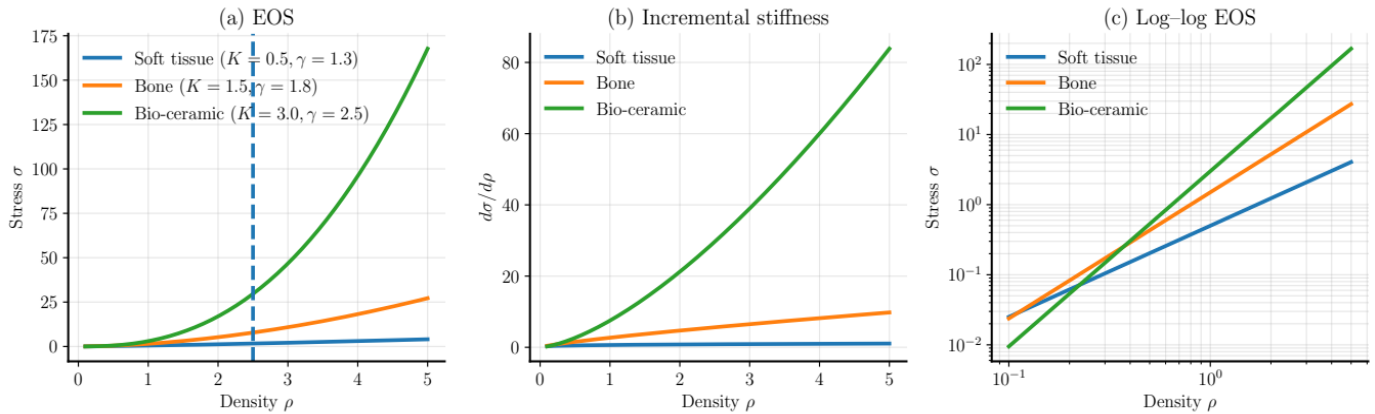


Figure 2: EOS-inspired mechanical behavior of biomedical materials. (a) Stress–density relation obtained from the constitutive law $\sigma = K\rho^\gamma$. (b) Incremental stiffness $d\sigma/d\rho$ demonstrating mechanical stability. (c) Log–log representation highlighting the power-law scaling of the EOS, analogous to representations commonly used in neutron-star equation-of-state studies.

To fully characterize the EOS-inspired constitutive behavior, both the stress–density relation and its derivative with respect to density are examined. The stress density curves represent the primary EOS, describing how internal stress develops as a function of material density. In contrast, the incremental stiffness $d\sigma/d\rho$ quantifies the local slope of the EOS and serves as a mechanical stability and rigidity indicator. The two quantities convey distinct physical information: the former defines the constitutive response and the latter assesses resistance to incremental densification. As shown in Figure 2(a), materials characterized by lower values of the rigidity parameter (K) and polytropic index (γ) exhibit gradual stress growth with increasing density, reflecting compliant behavior typical of soft tissues. In contrast, higher values of (K) and (γ) produce rapid stress amplification, indicative of strong resistance to densification as observed in bone and bio-ceramic materials. The corresponding incremental stiffness curves in Figure 2(b) remain strictly positive across the entire density range, satisfying the stability condition ($d\sigma/d\rho > 0$) and ensuring mechanical admissibility. The log–log representation in Figure 2(c) highlights the underlying power-law structure of the EOS, where the slope directly corresponds to the polytropic index (γ).

6.3 Phase-transition-like extensions

To model damage, remodeling, or abrupt stiffening, a piecewise EOS may be introduced,

$$\sigma = \begin{cases} K_1\rho^{\gamma_1}, & \rho < \rho_c \\ K_2\rho^{\gamma_2}, & \rho \geq \rho_c \end{cases} \quad (9)$$

where ρ_c represents a critical densification threshold. The critical density ρ_c marks the transition between soft and stiff behavior. The EOS is constructed such that stress (σ) is continuous at ρ_c . There is no discontinuity in the curve. Damage increases with density in the low-density regime due to active microstructural mechanisms such as pore collapse and void growth. Near the critical density, damage reaches a maximum. Beyond this point, densification reduces porosity and restricts further defect evolution, resulting in the stabilization or reduction of damage. Piecewise-polytropic EOS models are widely used to approximate realistic neutron star matter of different density regimes [21].

The piecewise EOS behavior illustrated in Figure 3 further extends the framework by enabling a transition between low-density (soft) and high-density (stiff) regimes. This transition, governed by a critical density (ρ_c) produces a continuous and physically consistent stress response, analogous to phase transitions in compact-star matter. The Figure 3(a) illustrates the variation of stress (σ) as a function of density (ρ) for three cases: Soft EOS, Stiff EOS, and Piecewise EOS. A critical density ρ_c separates two distinct physical regimes. Region I: $\rho < \rho_c$ (Soft EOS). For densities below the critical density, the piecewise EOS follows the soft EOS, given by: $\sigma = K_{\text{soft}}\rho^{\gamma_{\text{soft}}}$. Here the slope ($d\sigma/d\rho$) is small. Stress increases slowly with density. The material is highly compressible (soft). In the plot, the piecewise EOS overlaps with the soft EOS in this region, showing a gentle slope. Region II: $\rho > \rho_c$ (Stiff EOS). For densities above the critical density, the EOS transits to the stiff regime as $\sigma = K_{\text{stiff}}\rho^{\gamma_{\text{stiff}}}$. Here the slope

($d\sigma/d\rho$) is large. Stress increases rapidly with density. The material becomes difficult to compress (stiff). In this region,

the piecewise EOS coincides with the stiff EOS and appears much steeper.

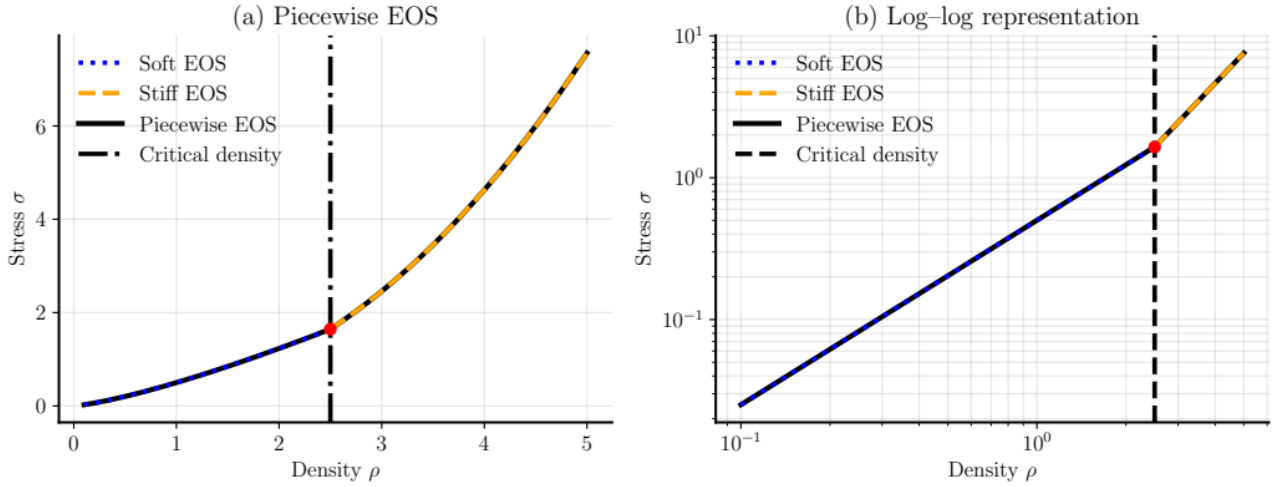


Figure 3: Piecewise polytropic equation of state. (a) Linear representation showing the soft, stiff, and combined EOS with the transition at the critical density. (b) Log-log representation of the piecewise EOS highlighting the change in power-law behavior across the density transition.

Log-Log Representation: In this plot (Figure 3(b)) both EOS appear as straight lines. The slope corresponds to the polytropic index equals to $-\gamma_{soft}$ for $\rho < \rho_c$ and $-\gamma_{stiff}$ for $\rho > \rho_c$. Hence, the piecewise EOS effectively models a system where matter is compressible at low densities (soft EOS) but becomes rigid at high densities (stiff EOS). The transition at ρ_c ensures a smooth physically consistent description of the system.

6.4 Parameter sensitivity analysis of the EOS

In order to further investigate the mechanical behavior predicted by the EOS-inspired constitutive framework, a parameter sensitivity analysis was performed. In particular, the influence of the polytropic index (γ) on the stress-density relation was examined. Physically, γ represents the collective effect of microstructural interactions within the biological material, including fiber connectivity, mineralization, and collagen network organization. To explore this dependence, the EOS relation $\sigma = K\rho^\gamma$ was evaluated for a fixed rigidity parameter ($K=1$) while varying the polytropic index (γ) over a

range 1.2, 1.6, 2.0, 2.5. These values span the transition from weakly nonlinear soft biological tissues to strongly stiffening hard biomaterials as shown in Figure 4(a). As γ increases, the stress-density relationship becomes increasingly nonlinear, with a pronounced steepening at higher densities. This indicates that γ primarily controls the compressibility of the medium, with larger values corresponding to a stiffer response under compression. In addition to the nonlinear index (γ), the rigidity parameter (K) controls the overall stiffness scale of the EOS. To investigate this effect, simulations were performed with a fixed ($\gamma=1.8$) while varying the rigidity parameter (K) as 0.3, 1.0, 2.0 as shown in Figure 4(b). In this case, the functional form of the curves remains unchanged, while their magnitude scales proportionally with K . Thus, K acts as a linear scaling factor that modulates the overall stress level without altering the intrinsic nonlinearity of the response. Collectively, these results highlight the distinct roles of the two parameters: γ governs the degree of nonlinearity in the equation of state, whereas K determines the absolute stiffness of the system.

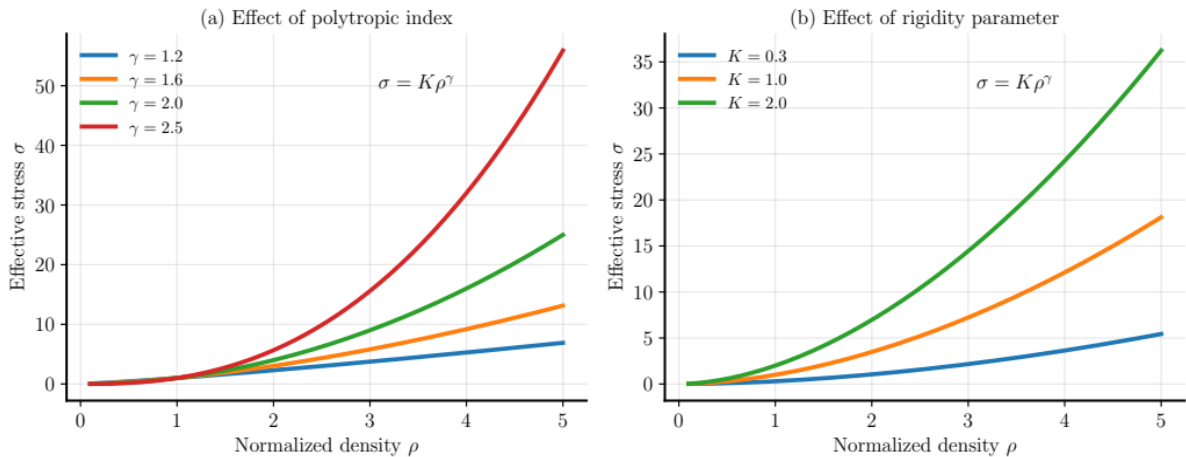


Figure 4: Parameter sensitivity of the polytropic equation of state. (a) Variation of effective stress with normalized density for different values of the polytropic index (γ). (b) Dependence of the equation of state on the rigidity parameter (K) for fixed γ .

6.5 Interplay of EOS parameters: Combined effect of K and γ

The combined influence of these parameters, as illustrated in Figure 5, demonstrates that materials with lower (γ) but higher (K) may exhibit stronger stress responses (panel(a))

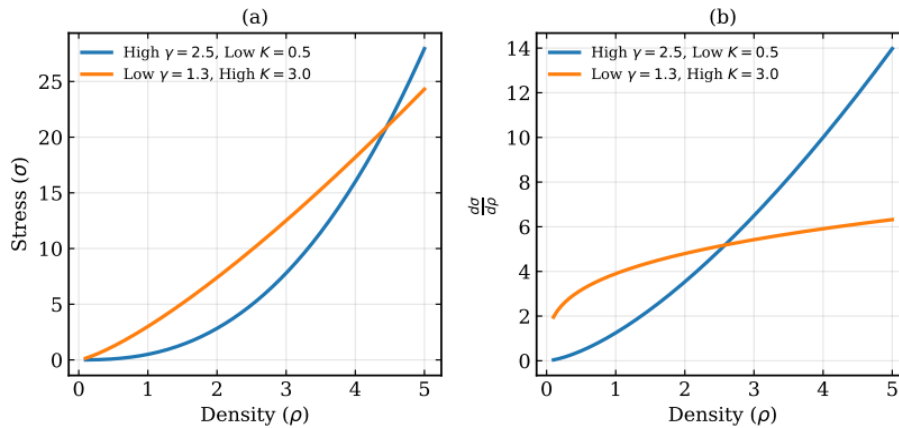


Figure 5: Two-panel comparison showing (a) stress–density relation and (b) incremental stiffness for two EOS.

6.6 Analogy between bio-material mechanics and astrophysical EOS

To further illustrate the conceptual analogy between biomaterial mechanics and astrophysical EOS models, we present a log–log comparison with a representative neutron-star polytropic EOS. The comparison between bio-material EOS model and a representative neutron star polytropic EOS highlights the structural similarity of their governing constitutive relations. In both cases stress or pressure follow a power law dependence on density characterized by stiffness

and non-linear response parameters. The Figure 6 demonstrates this analogy how EOS-inspired modeling approaches developed in astrophysics can be conceptually adapted to describe complex biomaterial mechanics. Finally, the structural similarity of the power-law relations becomes evident across systems of vastly different physical scales. Overall, the results confirm that EOS-inspired constitutive laws provide a compact and physically interpretable framework for differentiating and classifying biomedical materials.

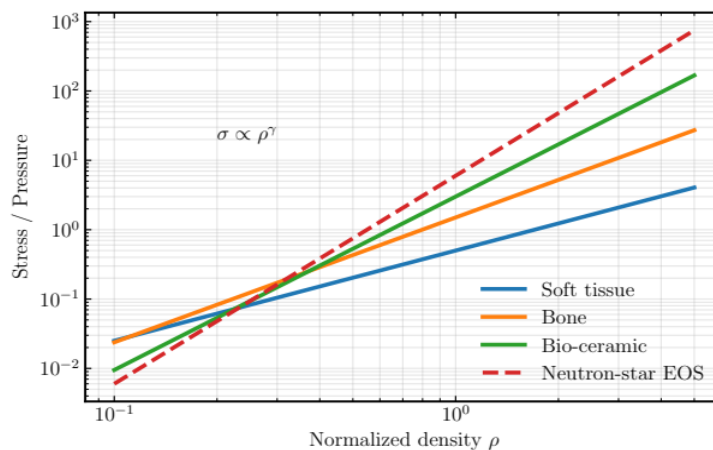


Figure 6: Log–log comparison between EOS-inspired constitutive relations for representative biomedical materials and a typical neutron-star polytropic equation of state.

7. Discussion, outcomes, and biomedical implications

7.1 Interpretation of numerical results

The numerical simulations demonstrate a clear mechanical distinction between soft biological tissues and hard biomaterials within the EOS-inspired framework as discussed above.

7.2 Stability and mechanical admissibility

A key outcome of the EOS-inspired framework is the explicit incorporation of stability conditions. The requirement of positive incremental stiffness, expressed as $d\sigma/d\rho > 0$, ensures mechanical admissibility across the modeled density range. All parameter sets considered in this study satisfy this condition, confirming the absence of nonphysical softening or instability.

7.3 Comparison with classical biomechanical models

Classical biomechanical models, including hyperelastic and exponential stress–strain formulations, typically require multiple fitted parameters and lack explicit stability constraints. In contrast, the EOS-inspired framework achieves comparable nonlinear behavior using a minimal parameter set with direct physical interpretation. While the present model does not explicitly account for anisotropy or viscoelasticity, it provides a unifying baseline description that can be systematically extended. As such, the EOS formulation may serve as a theoretical base upon which more detailed constitutive features can be incorporated.

7.4 Biomedical implications and outcomes

The outcomes of this study suggest several potential applications of EOS-inspired modeling in biomedical science. EOS parameters may serve as effective classifiers for distinguishing revealed differences between soft and hard biological materials. The framework provides interpreting pathological changes in tissue stiffness, such as fibrosis or tumor-induced stiffening. The model offers theoretical guidance for biomaterial design, where targeted EOS parameters could be selected to match or complement native tissue mechanics. Finally, the analytical nature of the framework makes it suitable for multiscale modeling and integration into computational biomechanics platforms. The parameter sensitivity analysis reinforces the physical interpretability of the EOS framework. As stated earlier that variations in γ capture changes in nonlinear stiffening behavior, whereas variations in K control the absolute stress scale. This separation of roles allows the EOS model to classify a wide range of biomedical materials using only two parameters. Such a compact representation is advantageous for modeling and computational biomechanical applications.

7.5 Limitations

Despite its conceptual strengths, the present framework is phenomenological and does not explicitly incorporate biological microstructure, time-dependent effects, or anisotropic behavior. Experimental calibration will be required to establish quantitative correspondence between EOS parameters and measurable material properties. Nevertheless, the goal of this work is not to replace established biomechanical models, but to introduce a unifying theoretical perspective inspired by dense-matter physics. Within the scope, EOS-based approach provides an extensible baseline.

8. Prospects for experimental verification

Although the present study focuses on theoretical modeling, the proposed EOS-inspired constitutive framework can in principle be validated through existing experimental techniques used in biomechanics and biomaterials research. Mechanical characterization of biological tissues is commonly performed using compression testing, indentation methods, and imaging-based elastography techniques. In these experiments, the mechanical response of a material is measured in terms of stress–strain or stiffness relations under controlled loading conditions. Within the EOS-inspired framework introduced in this work, the normalized density (ρ) represents an effective measure of structural packing, hydration level, or mineral content of the biological material. Experimental measurements

of stress response as a function of deformation or compaction may therefore be used to extract the effective EOS parameters K and γ through curve fitting of the relation $\sigma = K\rho^\gamma$. Advanced techniques such as atomic force microscopy (AFM), nanoindentation, and magnetic resonance elastography (MRE) provide high-resolution measurements of tissue stiffness at different spatial scales. These measurements can be interpreted within the EOS framework to obtain spatially varying rigidity parameters that characterize tissue heterogeneity. Future experimental work combining mechanical testing with density or microstructural imaging may therefore provide a direct pathway for validating and calibrating the proposed EOS-inspired constitutive model. High-resolution measurements of tissue stiffness can be obtained using atomic force microscopy and nanoindentation techniques [22, 23]. Imaging techniques such as ultrasound and magnetic resonance elastography provide spatial maps of tissue stiffness in vivo [24, 25].

9. Potential biomedical applications

The EOS-inspired modeling framework proposed in this study has several applications in biomedical science and biomaterials engineering. One important application is the characterization of pathological changes in tissue mechanics. Many diseases are associated with measurable changes in tissue stiffness; for example, fibrosis leads to abnormal stiffening of organs, while tumor growth often produces mechanically heterogeneous environments [26,27]. Within the EOS framework, such changes can be interpreted as variations in the rigidity parameter (K) and the nonlinear response index (γ). The framework also provides a basis for the design of synthetic biomaterials. By tuning EOS parameters, it may be possible to engineer materials with mechanical responses that closely match those of native tissues, which is particularly relevant in tissue engineering and implant design. In addition, the model may contribute to computational biomechanics and medical imaging. Techniques such as ultrasound elastography and magnetic resonance elastography generate spatial maps of tissue stiffness. Interpreting these data in terms of EOS parameters offers a compact and physically motivated description of tissue mechanical behavior. Finally, the EOS-inspired approach supports multiscale modeling by linking microscopic structural properties to macroscopic mechanical response through a small set of physically interpretable parameters. This capability makes the framework particularly attractive for integrated modeling of complex biological systems.

10. Conclusions

In this work, an (EOS)-inspired theoretical framework has been developed for modeling the mechanical behavior of biomedical materials. By mapping the pressure–density relation used in neutron star physics to an effective stress–density constitutive law, a polytropic EOS analogue was formulated to describe both soft biological tissues and hard biomaterials. The numerical analysis shows that variations in the rigidity parameter (K) and the polytropic index (γ) naturally reproduce the qualitative differences between soft-like and stiff biological matter. Soft tissues exhibit gradual stress evolution, whereas hard biomaterials display pronounced nonlinear stiffening. The introduction of a piecewise EOS further enables the modeling of phase-transition–like behavior associated with densification, damage, or structural

remodeling. Although the model is phenomenological, it provides a compact, physics-inspired framework with explicit mechanical admissibility conditions derived from compact-star stability criteria. This approach establishes a conceptual bridge between dense matter astrophysics and biomedical material science, offering a unified analytical language for nonlinear material response.

Future work may extend this framework by incorporating anisotropic, viscoelastic, and temperature-dependent effects, as well as by calibrating EOS parameters against experimental measurements of biological tissues and biomaterials. Such developments would enhance the applicability of the model in both theoretical and practical contexts.

Authors' contributions

The author read and approved the final manuscript.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

References

- [1] R.C. Tolman, Static solutions of Einstein's field equations for spheres of fluid, *Phys. Rev.* **55** (1939) 364–373.
- [2] J.R. Oppenheimer, G.M. Volkoff, On massive neutron cores, *Phys. Rev.* **55** (1939) 374–381.
- [3] S.L. Shapiro, S.A. Teukolsky, Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects, Wiley, New York (1983).
- [4] J.M. Lattimer, M. Prakash, The physics of neutron stars, *Science* **304** (2004) 536–542.
- [5] Y.C. Fung, Biomechanics: Mechanical Properties of Living Tissues, 2nd edn., Springer, New York (1993).
- [6] J.D. Humphrey, Cardiovascular Solid Mechanics: Cells, Tissues, and Organs, Springer, New York (2002).
- [7] G.A. Holzapfel, Nonlinear Solid Mechanics: A Continuum Approach for Engineering, Wiley, Chichester (2000).
- [8] B.D. Ratner, A.S. Hoffman, F.J. Schoen, J.E. Lemons (Eds.), Biomaterials Science: An Introduction to Materials in Medicine, 3rd edn., Academic Press, San Diego (2013).
- [9] B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), GW170817: Observation of gravitational waves from a binary neutron star inspiral, *Phys. Rev. Lett.* **119** (2017) 161101.
- [10] B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), GW170817: Measurements of neutron star radii and equation of state, *Phys. Rev. Lett.* **121** (2018) 161101.
- [11] M.C. Miller et al., PSR J0030+0451 mass and radius from NICER data and implications for the properties of neutron star matter, *Astrophys. J. Lett.* **887** (2019) L24.
- [12] T.E. Riley et al., A NICER view of PSR J0030+0451: Millisecond pulsar parameter estimation, *Astrophys. J. Lett.* **887** (2019) L21.
- [13] R.F. Tooper, General relativistic polytropic fluid spheres, *Astrophys. J.* **142** (1965) 1541–1562.
- [14] S. Chandrasekhar, An Introduction to the Study of Stellar Structure, University of Chicago Press, Chicago (1939).
- [15] F. Özel, P. Freire, Masses, radii, and the equation of state of neutron stars, *Annu. Rev. Astron. Astrophys.* **54** (2016) 401–440.
- [16] J.Y. Rho, L. Kuhn-Spearing, P. Zioupos, Mechanical properties of bone, *Med. Eng. Phys.* **20** (1998) 92–102.
- [17] N.K. Glendenning, Compact Stars: Nuclear Physics, Particle Physics, and General Relativity, 2nd edn., Springer, New York (2000).
- [18] B.K. Harrison, K.S. Thorne, M. Wakano, J.A. Wheeler, Gravitation Theory and Gravitational Collapse, University of Chicago Press, Chicago (1965).
- [19] R.W. Ogden, Large deformation isotropic elasticity: On the correlation of theory and experiment for incompressible rubberlike solids, *Proc. R. Soc. A* **326** (1972) 565–584.
- [20] P. Haensel, A.Y. Potekhin, D.G. Yakovlev, Neutron Stars 1: Equation of State and Structure, Springer, New York (2007).
- [21] J.S. Read et al., Constraints on a phenomenologically parameterized neutron-star equation of state, *Phys. Rev. D* **79** (2009) 124032.
- [22] E.M. Darling et al., Viscoelastic properties of human mesenchymal stem cells, *Biophys. J.* **90** (2006) 1384–1394.
- [23] A.J. Engler et al., Matrix elasticity directs stem cell lineage specification, *Cell* **126** (2006) 677–689.
- [24] R. Muthupillai et al., Magnetic resonance elastography by direct visualization of propagating acoustic strain waves, *Science* **269** (1995) 1854–1857.
- [25] A.P. Sarvazyan et al., Elasticity imaging: Methods and applications, *Rep. Prog. Phys.* **74** (2011) 066601.
- [26] M.J. Paszek et al., Tensional homeostasis and the malignant phenotype, *Cancer Cell* **8** (2005) 241–254.
- [27] D.E. Discher, P. Janmey, Y.L. Wang, Tissue cells feel and respond to the stiffness of their substrate, *Science* **310** (2005) 1139–1143.