Düzce University
Journal of Science & Technology

Research Article

Exploring the Multifaceted Dynamics of Cartilage: A Comparative Modeling Study

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DOI: 10.29130/dubited.1347207

ABSTRACT

Cartilage numeric models play a vital role in advancing our understanding of cartilage mechanics, disease progression, and the development of clinical interventions. The aim of this study is to investigate the influence of different mathematical models on cartilage mechanical behavior over time. A comparative analysis was conducted across three scenarios: the single-phase, biphasic, and fibril-reinforced poroelastic models. To understand how cartilage behaves over time, a 1000-second ramp relaxation displacement was applied. The findings reveal that the single-phase model falls short of capturing the time-dependent characteristics of cartilage. Conversely, the inclusion of fluid and collagen fibrils within the cartilage model significantly enhances cartilage resilience and enables the cartilage to behave non-linearly. The results presented herein make a substantial contribution to a deeper and more holistic comprehension of cartilage's dynamic behavior under compressive loads, shedding light on the intricate interplay between fluid pressure and fibril reinforcement.

Keywords: *Single-phase, Biphasic, Fibril-reinforced, Cartilage, Finite Element Analysis*

Kıkırdağın Çok Yönlü Dinamiklerinin İncelenmesi: Karşılaştırmalı Modelleme Çalışması

ÖZ

Kıkırdak sayısal modelleri, kıkırdak mekaniği, hastalık ilerlemesi ve klinik müdahalelerin geliştirilmesi konusundaki anlayışımızı ilerletmede hayati bir rol oynamaktadır. Bu çalışmanın amacı, farklı matematiksel modellerin zaman içinde kıkırdak mekanik davranışı üzerindeki etkisini araştırmaktır. Üç senaryoda karşılaştırmalı bir analiz yapılmıştır: tek fazlı model, bifazik model ve fibril takviyeli poroelastik model. Kıkırdağın zaman içinde nasıl davrandığını anlamak için 1000 saniyelik bir rampa gevşeme deplasmanı uygulanmıştır. Bulgular, tek fazlı modelin kıkırdağın zamana bağlı özelliklerini yakalamakta yetersiz kaldığını ortaya koymaktadır. Buna karşılık, kıkırdak modeline sıvı ve kolajen fibrillerin dahil edilmesi kıkırdak direncini önemli ölçüde artırmakta ve kıkırdağın doğrusal olmayan bir şekilde davranmasını sağlamaktadır. Burada sunulan sonuçlar, sıvı basıncı ve fibril takviyesi arasındaki karmaşık etkileşime ışık tutarak, kıkırdağın basınç yükleri altındaki dinamik davranışının daha derin ve daha bütünsel bir şekilde anlaşılmasına önemli bir katkı sağlamaktadır.

Anahtar Kelimeler: *Tek-fazlı, Bıfazik, Fibril-takviyeli, Kıkırdak, Sonlu Elemanlar Analizi*

Received: 21/08/2023, Revised: 04/10/2023, Accepted: 02/11/2023

I. INTRODUCTION

Knee cartilage, a remarkable connective tissue, is pivotal in maintaining joint function and supporting load-bearing activities in the human body [1]. Cartilage, comprising a complex matrix of solid and fluid phases, exhibits intricate mechanical properties [2, 3]. The solid phase predominantly comprises proteoglycans and collagen [4]. Collagen fibrils interlace with proteoglycans, forming a porous scaffold accommodating the fluid phase [5]. The fluid phase within cartilage plays a multifunctional role, influencing its mechanical properties, nutrient exchange, and lubrication [6]. The interactions between the solid and fluid phases are essential for maintaining the tissue's compressive stiffness and distributing loads efficiently [7]. Collagen fibrils provide resistance against tensile forces, while proteoglycans in the matrix retain water, creating a swelling pressure that counteracts compressive loads. This dynamic equilibrium ensures cartilage resilience under various physiological conditions. Understanding the interplay between the solid and fluid phases, particularly the role of collagen, is crucial for unravelling the mechanisms behind cartilage biomechanics [8]. For this reason, many experimental [9-12] and numerical studies [13-15] have been conducted on cartilage.

Cartilage mechanics has been extensively illuminated through the amalgamation of finite element (FE) models and empirical evidence [16-18]. Predominantly, the mathematical underpinnings of these investigations have involved single-phase models, where the tissue is perceived as a solid entity [19-21]. These models, albeit elementary, encapsulate the foundational behaviour of articular cartilage by considering solely its solid phase. This approach, however, falls short of encapsulating the intricate fluid exudation dynamics intrinsic to cartilage. Nonetheless, this model finds utility in situations characterized by instantaneous loading, where the tissue promptly attains equilibrium. The biphasic and poroelastic models, derived from the Biot theory of soil consolidation [22], represent second-generation models for capturing flow-dependent phenomena like fluid exudation and imbibition [23]. In biphasic/poroelastic renditions, the cartilage's collagen fibrils and proteoglycan matrix, constituting the solid matrix, are encompassed by a solitary stiffness coefficient. However, a fibril-reinforced biphasic/poroelastic framework imparts distinction, calculating solid matrix stiffness across two constituents: the fibrillar network (collagen fibrils) and the non-fibrillar matrices (proteoglycan) [24]. The non-fibrillar matrix forms a continuous porous element, symbolizing the proteoglycan matrix, whereas the fibril network mirrors the collagen fibrils. Notably, the fibril architecture's role is limited to resisting tensile forces, not compression loads. Conversely, the non-fibrillar matrix shoulders tensile and compressive loads within the tissue.

This study compared the efficacy of cartilage numerical models, single-phase, biphasic, and fibril-reinforced poroelastic, using a 2D FE axisymmetric tissue model subjected to compressive forces. Incorporating various mathematical models to represent cartilage mechanics provides a comprehensive understanding of its behaviour under physiological conditions. This diversity of models enriches our insights, enables more accurate predictions, and facilitates advancements in diagnostics, treatment strategies, and biomechanical research.

II. MATERIAL and METHOD

A. CONSTITUTIVE EQUATIONS for CARTILAGE MODELS

Derived from Hooke's linear elastic model for solid materials, the single-phase model embodies a fundamental relationship between stress and strain [25]. This relationship parallels a spring anchored at one end and subjected to compression or elongation at the other. The essence of Hooke's model can be concisely encapsulated as follows:

$$\sigma = E\varepsilon \tag{1}$$

where σ is stress, ε is strain, and E is elastic (Young's) modulus. The biphasic model represents a longstanding approach to fluid-saturated tissue dynamics, encompassing the intricate motion of intra-articular fluid [25]. Within the framework of biphasic theory, both the solid matrix and the fluid are posited as intrinsically incompressible and non-dispersive. The main aspect of the theory lies in the fluid flow dynamics within the tissue. The constitutive equations governing this interplay, encompassing the stress-strain relationships for the solid, fluid, and holistic tissue, are encapsulated as follows:

$$\sigma_t = \sigma_s + \sigma_f = -pI + \sigma_E \tag{2}$$

where σ_s, σ_f and σ_t are the solid, fluid, and total stress tensors, respectively. p symbolizes the fluid pressure, I represent the unit tensor, and σ_E denotes the effective solid tensor. In the context of the fibril-reinforced biphasic model, the mechanical response of tissues under loading is influenced not only by the isotropic biphasic matrix but also by the presence of the fibril network (collagen network) [23]. Consequently, the cumulative stress can be succinctly expressed as follows:

$$\sigma_t = \sigma_{nf} + \sigma_{fibril} - pI \tag{3}$$

where σ_{nf} and σ_{fibril} are the non-fibril and fibril network tensions, respectively.

$$\sigma_{fibril} = A\varepsilon + B\varepsilon^2 \tag{4}$$

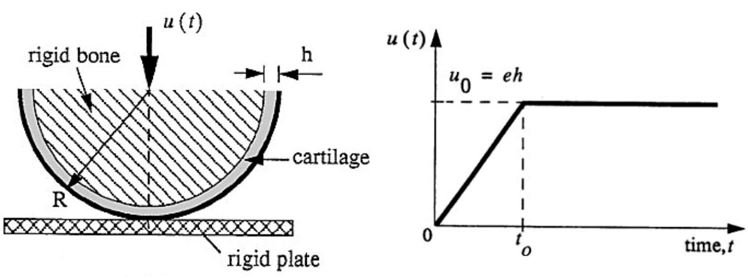
A and B represent material constants. These are numerical values that characterize a material's behavior under uniaxial (tensile) tests. These constants are typically determined through experimentation and analysis [26, 27].

B. 2D FE AXISYMMETRIC GEOMETRY and SOFT TISSUE MATERIAL PROPERTIES

The 2D axisymmetric geometry described by Wu et al. [28] was used in this study to symbolize the knee joint (

Figure 1a). The 2D knee joint model comprises a rigid bone and a rigid plate, along with a deformable sheet with a thickness of h=1mm to represent the soft cartilage. The spherical cartilage radius (R) was 399mm and was connected to the rigid plate with the *ABAQUS/Standard 2020* tie option. The rigid plate remained stationary, while the rigid bone was permitted to move vertically concerning the plate. Within the simulated stress-relaxation tests, the spherical bone's motion against a rigid plane adheres to a predetermined displacement history, as exemplified by the controlled movement depicted in

Figure 1b. This movement entails a ramp compression phase at t_0=100s, succeeded by a subsequent relaxation period spanning t=900s. The maximum displacement achieved was 0.08 (u_0), corresponding to compression ratios expressed as e = 8%. The same load and boundary conditions in the study [28] were applied in the present study. This approach was to compare our FE results with the analytical results of the study [28].



(a) *(b)*

Figure 1. ***(a)*** *2D axisymmetric geometry,* ***(b)*** *History of rigid bone motion [28].*

As depicted in

Figure 1a, the contact area lies on the axis of symmetry, which enables us to simulate only half of the model to achieve meaningful results, thus saving unnecessary computational time; consequently, the horizontal length of the three sections was established at 35mm (

Figure 2).

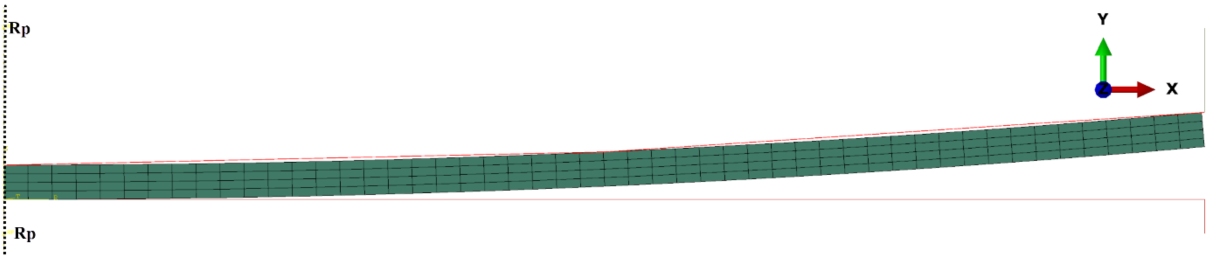


Figure 2. *In the finite element model's geometry, the bone and the rigid plate are denoted by the red line, and the cartilage by the green mesh, with yellow reference points (Rp) affixed to each rigid segment.*

The foundational model comprised 8 layers of elements radially and 100 elements circumferentially, resulting in a combined count of 800 elements. While the single-phase model employed linear quadrilateral elements (CAX4R), the biphasic and fibril-reinforced poroelastic models for quadratic quadrilateral porous elements (CAX8P). The number of elements was selected based on previous mesh density analysis [29] to ensure dependable results.

The bone was treated as rigid due to its considerable stiffness compared to the cartilaginous tissue. To replicate the cartilage's mechanical response during time-dependent compressive motion, single-phase, biphasic, and fibril-reinforced poroelastic models for soft tissue were discussed in the present study. The cartilage was regarded as an elastic isotropic material in the single-phase model. However, the biphasic model considers it viscoelastic to accommodate the fluid and solid phases. A porous permeability of 0.002mm^4/Ns was assumed, being isotropic. In contrast, the fibril-reinforced poroelastic model introduced fibrils along both horizontal and vertical axes to incorporate the effects of collagen. These fibrils were assumed to be orthotropic. Table 1 provides the respective material properties of cartilage for each model, and material properties were obtained in the literature [3].

Table 1. *Cartilage material properties (The fibril orientation was considered orthotropic. The horizontal axis is represented by “x”, while the vertical axis is represented by “y”.)*

Cartilage model	**Single-phase (Eq. 1)**	**Biphasic (Eq. 2)**	**Fibril-reinforced poroelastic (Eq. 3 and 4)**
Young’s Module (MPa)	0.50	0.50	0.50
Poisson’s ratio	0.3	0.3	0.3
Permeability (mm^4/Ns)	-	0.002	0.002
Void ratio	-	4	4
Material constant A (MPa)	-	-	1.38 (x) 0.41 (y)
Material constant B (MPa)	-	-	367.14 (x) 110.14 (y)

The method of surface-to-surface discretization was chosen for contact identification, with the *ABAQUS/Standard* small sliding option employed for the slide formulation, enabling substantial deformations of contacting bodies; this choice is predicated on the assumption of relatively small sliding between surfaces. Notably, the NLGEOM option was omitted in the *ABAQUS/Standard* finite element analysis to adhere to the small deformation theory, while a kinematic constraint was approximated to prevent contact overclosure, achieved through the linear penalty method that assigns contact pressure values to each surface node. A surface friction coefficient of 0.02 was adopted as a value within the typical range observed in human articular joints [30].

The *ABAQUS/Standard* analysis incorporated a soil consolidation procedure to replicate the biphasic and fibril-reinforced poroelastic models' behaviour involving solid-fluid interactions. Cartilage surfaces were chosen to be sealed to facilitate comparison with theoretical solutions [28].

III. RESULTS and DISCUSSIONS

In the present study, three commonly employed cartilage models within the existing literature, namely the single-phase, biphasic, and fibril-reinforced poroelastic models, were subjected to a comparative analysis of their mechanical responses under an 8% compression strain.

The fibril-reinforced poroelastic model exhibited the highest recorded reaction force within the range of models (

Figure 3). At the 100^{th} second, corresponding to the maximal displacement, the reaction forces were measured at 5.37N for the single-phase model, 109N for the biphasic model, and notably higher at 369N for the fibril-reinforced poroelastic model, which these results are consistent with the results of the literature [31]. These findings highlight the magnifying impact of integrating fluid effects into the cartilage model, resulting in an increased reaction force, and the supplementary enhancement achieved through the introduction of fibril effects, further amplifying the reaction force. Similarly, the peak of contact pressure (3.18MPa) was attained within the fibril-reinforced model, in contrast to the pressures of 0.06MPa observed in the single-phase model and 0.8 MPa in the biphasic model. These findings demonstrate that the interplay of fluid and collagen within the cartilage contributes to an augmented resilience of the cartilaginous tissues.

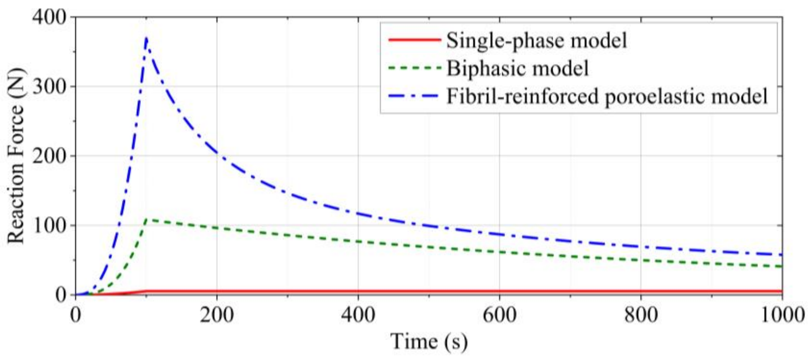


Figure 3. *Reaction forces on the reference point of the rigid plate after applying the compression force.*

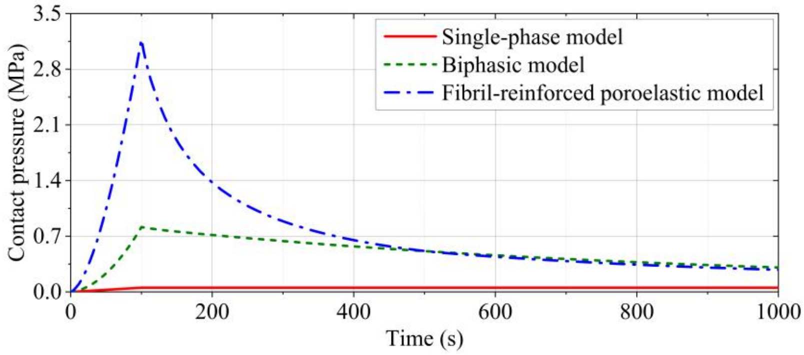


Figure 4. *Temporal Variations in Contact Pressure.*

Figure 4 shows the maximum contact variations over time for each model. The maximum contact pressures were obtained by the *ABAQUS* CPRESS query option from the element of each model where the contact pressure reached the maximum. Since biphasic and fibril-reinforced poroelastic models account for the fluid effect, the maximum contact pressure decreased with time in these models thanks to fluid exudation from cartilage. In contrast, contact stress reduction was not observed in the single-phase model, which only considers the solid phase of soft tissue.

Notably, while

Figure 3 and

Figure 4 could not encapsulate the temporal dynamics inherent in the single-phase model, the biphasic and fibril-reinforced poroelastic models effectively showcased the intricate temporal variations characterizing cartilage mechanics. This phenomenon became evident through the distinct manifestation of a relaxation effect, where the mechanical response of the cartilage demonstrated a gradual and noticeable decline in force over time. In

Figure 3 and

Figure 4, when examined in terms of relaxation times, it is observed that the fibril-reinforced model had a faster relaxation time despite generating higher stress. This intriguing observation may be attributed to the influence of collagen fibers in soft tissues arising from their different structural characteristics. Collagen fibers play a crucial role in imparting structural resilience to tissues. They exert a constraining effect on the mobility and deformation of tissues. Moreover, collagen fibrils provide the greatest resistance against tensile forces [32-34]. This collective effect, possibly facilitated by the complex collagen fibril network, could contribute to a faster relaxation response, enhancing the tissue's intrinsic ability to return to its initial configuration after deformation. However, as the fluid flows move the collagen fibrils, it applies drag forces on them. These forces are expected to cause the fluid to move more slowly and have a longer relaxation period [35]. The reason for this significant difference in our results may be interesting to investigate.

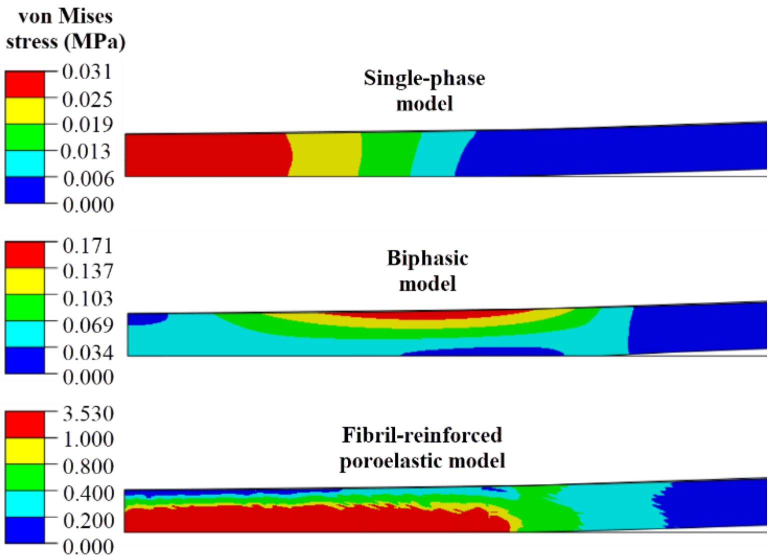


Figure 5. *von Mises stress distributions in cartilage models under 0.08mm compression at 100th seconds. For the convenience of readers, only the partial, where the pressure occurred, has shown instead of the whole cartilage. The reference axis is on the left side.*

There were also significant differences in von Mises stress distribution between the models (

Figure 5). The high-pressure distribution was centred around the reference axis in the single-phase, while in the other two models, it occurred in different regions of the cartilage. In addition, as with the contact pressure and reaction force, the highest von Mises stress value occurred in the fibril-reinforced model, followed by the biphasic and the single-phase models, respectively. These results show that the single-phase model fails to capture the time-dependent non-linear behaviour of the cartilage under the relaxation scenario. However, the fluid flow considered in the other two models allowed for stress distribution throughout the tissue, ensuring the nonlinear behaviour of the cartilage. This finding aligns with previous studies emphasizing the non-linear behaviour of cartilage under compressive forces [3, 23]. It is worth noting that in the biphasic model, the highest stress distribution occurred in the upper region of the cartilage, away from the reference region. Conversely, in the fibril-reinforced model, the maximum stress distribution began in the lower region of the cartilage, extending from the reference line. This distinction may be attributed to the downward movement of fluid as displacement increases over 100 seconds. During constant displacement (100s-1000s), collagen fibrils restrict fluid passage to the upper layers through drag forces.

Table 2. *Contact length between cartilage and rigid plate at the 100th second.*

Maximum contact length	
Single-phase	195mm
Biphasic	318mm
Fibril-reinforced poroelastic	227mm

Table 2 shows the contact length between the cartilage surface and the rigid plate when the compression force reaches its maximum. The remarkable result occurred in the biphasic model. The reaction force, contact pressure, and von Mises stress in the biphasic model are less than in the fibril-reinforced poroelastic model, but the contact length is 40% greater. This result proves collagen fibrils are an important inhibitory factor in cartilage deformation. Collagen fibrils prevented the transverse elongation of the cartilage under compressive force, resulting in less contact length.

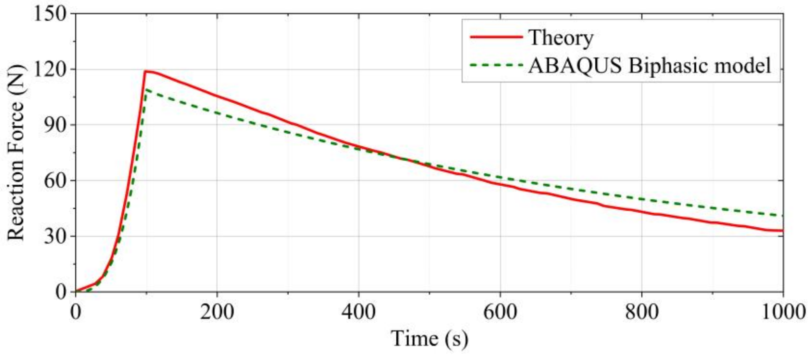


Figure 6. *Comparison of the theoretical results [28] with the analysis results predicted in the presented study.*

In this study, various mathematical models were applied to the cartilage model derived from the research conducted by Wu et al. [28]. In their investigation, they examined the behaviour of the biphasic cartilage model under a 0.08mm compression displacement through theoretical calculations. Figure 6 demonstrates a substantial alignment between the reaction force obtained from our finite element analysis and the theoretical reaction force outlined in their study.

The limitation of this study may be the use of 2D cartilage models instead of 3D cartilage models. A 2D model represents cartilage as a flat, two-dimensional structure, neglecting the complex 3D geometry of real cartilage tissue. Moreover, in some areas of cartilage, collagen fibril is crucial in its mechanical behaviour. 3D models can better represent the orientation and reinforcement effect of these fibrils. Despite all these, the reason for choosing a 2D dimensional model in our study was to increase the reliability of the FE analysis results by comparing them with the theoretical results in the literature. Moreover, it has been clearly emphasized in the studies on 3D cartilage models that taking fibril and fluid into account significantly affects cartilage mechanics. Using a 2D model may be a simple way to compare mathematical model performances.

IV. CONCLUSION

A comparative analysis was performed in three cases to investigate the mathematical cartilage model effect: single-phase model, biphasic model, and fibril-reinforced poroelastic model. To capture the behaviour of the cartilage concerning time, a ramp relaxation displacement of 1000 seconds was applied. The obtained results have demonstrated that the single-phase model fails to capture the time-dependent behavior of cartilage. However, incorporating the effects of fluid and collagen fibrils in the cartilage model has clearly shown a significant increase in cartilage resilience. The results presented herein contribute significantly to an enhanced and comprehensive comprehension of the dynamic behavior exhibited by cartilage under compressive loads, furnishing insights into the intricate interplay between fluid pressure and fibril reinforcement.

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