

# Dynamic Response of Femoral Cartilage in Knees With Unicompartamental Osteoarthritis

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## ABSTRACT

The objective of the present work was to determine the dynamic indentation response, stiffness and relaxation curves for the shear and the bulk modulus of femoral knee cartilage with no visual damage in cases under unicompartamental osteoarthritis.

A cyclic displacement of 0.5 mm in axial direction was applied with a 3 mm plane-ended cylindrical indenter at specific points in the femoral knee cartilage specimens of seven patients with unicompartamental osteoarthritis (UOA). The indentation force over time was recorded and next the maximum stiffness in all cycles was obtained and compared. Also, the relaxation curves for the shear and the bulk modulus of cartilage were obtained in this work.

A decrease in the maximum indentation force was observed comparing between indentation cycles; it was of  $6.75 \pm 0.71\%$  from cycle 1 to cycle 2 and  $4.70 \pm 0.31\%$  for cycle 2 to cycle 3. Stiffness values changed with a mean of  $3.35 \pm 0.39\%$  from cycle 1 to cycle 2 and  $1.40 \pm 0.71\%$  from cycle 2 to cycle 3. Moreover, relaxation curves for the shear modulus and the bulk modulus showed the nonlinear behavior of articular cartilage with UOA.

Our results showed that cartilage specimens with no visual damage in UOA preserve a nonlinear viscoelastic behavior and its stiffness increases through the loading cycles. Our work provides experimental values for generating a more realistic cartilage behavior than those currently used in computer cartilage models for the study of UOA.

Keywords: Osteoarthritis, cartilage, dynamic response, biomechanics.

## RESUMEN

El objetivo de este trabajo fue determinar la respuesta dinámica de indentación, la rigidez y las curvas de relajación para módulo cortante y volumétrico de cartílago femoral de rodilla con daño no visual en casos con osteoartritis unicompartamental.

Se aplicó un desplazamiento cíclico de 0.5 mm en dirección axial con un indentador cilíndrico plano de 3 mm en puntos específicos de los especímenes de cartílago femoral de rodilla de siete pacientes con osteoartritis unicompartamental (OAU). La fuerza de indentación a través del tiempo fue registrada, obteniéndose y comparándose la máxima rigidez en todos los ciclos. Además, en este trabajo se obtuvieron las curvas de relajación para el módulo cortante y volumétrico de cartílago.

Se observó una disminución en la fuerza de indentación máxima comparando entre los ciclos de indentación; ésta fue  $6.75 \pm 0.71\%$  del ciclo 1 al 2, y  $4.70 \pm 0.31\%$  del ciclo 2 al 3. Los valores de rigidez cambiaron  $3.35 \pm 0.39\%$  entre el ciclo 1 y 2, y  $1.40 \pm 0.71\%$  entre el ciclo 2 y 3. Además, las curvas de relajación para el módulo cortante y volumétrico mostraron el comportamiento no lineal del cartílago articular con OAU.

Los resultados mostraron que los especímenes de cartílago con daño no visual en OAU preservan un comportamiento viscoelástico no lineal y su rigidez se incrementa a través de los ciclos de carga. Este trabajo provee valores experimentales para generar un comportamiento de cartílago más real que el utilizado actualmente en modelos computacionales de cartílago para el estudio de OAU.

## 1. Introduction

The articular cartilage has a finite deformation due to physiological load [1] and works as a mechanical damping surface in the synovial joints [2, 3]. These kinds of joints are exposed to degenerative diseases like osteoarthritis, where the articular cartilage wears out and causes musculoskeletal pain and disability. In these cases, osteoarthritis of the entire knee is distinguished from osteoarthritis of one compartment (unicompartmental osteoarthritis), where one compartment is damaged and the other one is considered as healthy. However, the visual and histological appearance of tissue is not a good indicator of performance in a synovial joint and it requires a biomechanical evaluation [4, 5].

Several works [6-11] have reported the analysis of the cartilage biomechanical behavior, they include different studies such as the dynamic behavior of biphasic cartilage model [6], the effect of mechanical dynamic force in the cartilage metabolism [7], the dynamic elastic modulus [8], the dynamic deformation of patellar cartilage [9], the effect of dynamic compression loads in proteins and molecules to repair cartilage [10], and the mechanical behavior of cartilage under tension fatigue loading [11]. These studies have been realized applying cyclic loading by unconfined compression in human, bovine and porcine healthy cartilage.

However, some works have used static load to determine the mechanical properties [2, 12-16] and thickness [2, 17-19] of healthy cartilage and tibial cartilage with osteoarthritis [4]. At present, there are no reported studies about the dynamic mechanical behavior of femoral cartilage with any visual damage in unicompartmental knee osteoarthritis. These studies are necessary in cases of surgery for unicompartmental knee replacement due to the cartilage with no visual damage is preserved and it could have an undesirable biomechanical response. It could impact the mechanical performance of the knee, unicompartmental prosthesis and life quality of the person. Therefore, we present a study of the dynamic response of femoral knee cartilage in specimens with unicompartmental osteoarthritis. Our work provides experimental values of indentation force and stiffness through cycles and relaxation curves for

the shear modulus and the bulk modulus over time. These experimental values can be used for generating a more real cartilage behavior than those currently used in computer cartilage models for the study of UOA [2].

## 2. Materials and methods

### 2.1 Specimens

The specimens were removed during surgery for total knee replacement so it was possible to obtain cartilage with subchondral bone of femoral compartment (see Figure 1). Seven femoral knee specimens were obtained from female patients diagnosed with unicompartmental osteoarthritis, which came from a non-cadaveric population with ages ranging from 59 to 73 years old. The knee specimens have been donated by patients under administrative control of the Mexican Social Security Institute (IMSS) for scientific and medical research.

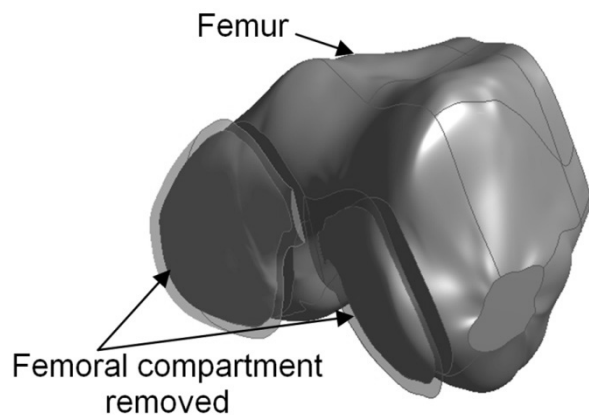


Figure 1. Schematic specimens removed with cartilage and subchondral bone during surgery for total knee replacement.

### 2.2 Groups

Relaxation and cyclic indentation tests on cartilage of lateral femoral compartments were performed using an impermeable plane-ended cylindrical indenter. Five points on the surface of each femoral compartment were selected for cartilage dynamic testing. Each point was identified and associated with a group (Figure 2), named and described as follows:

- AP: anterior point.
- CP: central point.
- LP: lateral point.
- MP: medial point.
- PP: posterior point.

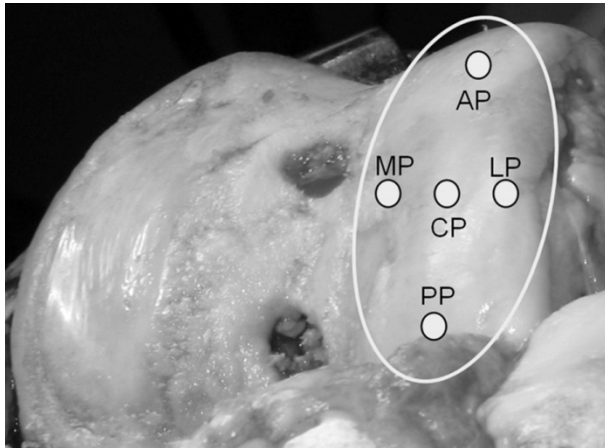


Figure 2. Test points in femoral knee compartment.

### 2.3 Indentation test

A common technique for measuring the compressive properties of cartilage is through indentation [20, 21]. For this procedure, a probe of specified geometry (e.g., cylindrical, spherical or pyramidal) is indented into a material. Elastic properties of different materials can be obtained through this technique, which has also been developed to characterize the time-dependent properties of viscoelastic materials [22].

Our test of cartilage indentation has been performed using similar testing protocols of several works [6, 21, 23] and the mathematical analysis for indentation tests of articular cartilage reported by Hayes et al. [24]. Therefore, we determined instantaneous stiffness values rather than those in steady state because (during the immediate response of the cartilage after application of load) it behaves as an incompressible elastic material of a single phase. Since the fluid in the cartilage is unable to flow due to the short time of load application [21, 23, 25]. In order to achieve this, a rapid rate of load application is required to reduce or eliminate the relaxation effect.

Cartilage specimens with subchondral bone were tested without doing any additional cutting, which preserves the specimen free of any induced mechanical effects on the test site. Thus, a cyclic displacement of 0.5 mm was applied to the cartilage in axial direction with a 3 mm diameter rigid indenter attached to a 500 N load cell of a materials testing machine (CHATILLON® TCD200). This displacement corresponds to a real physiological displacement of 25-30% [1]. The indenter diameter should be at least one third of the specimen diameter size (plugs of cartilage with subchondral bone) to avoid the stiffness effect of the subchondral bone on cartilage measurements, which has been suggested in previous analysis [4, 21]. In this work, we did not take plugs of cartilage to avoid any induced mechanical effects on the test site; we tested the complete femoral compartment, which was done in previous studies on tibia [12]. Thus, the small size of the indenter diameter in this work is less than one third of the indentation area on the complete cartilage specimens.

The physiological normal state of cartilage hydration was considered in this work. The cartilage specimens were hydrated regularly with saline solution to prevent dehydration of the indentation surface and cells during the whole test. Each specimen was fixed in a platform where it could be carefully adjusted in any position so the cartilage surface was just in contact and perpendicular to the longitudinal axis of the indenter (see Figure 3). In order to avoid the influence between two indentation test points in the specimen, we waited for five to eight minutes for total recovery of the indented surface before starting with the next point. About five minutes for total recovery of the indented surface was observed and reported by Thambayah A. et al. [12] in cartilage of tibia. During this time, the specimen was hydrated to prevent dehydration of cells. The displacement cycles are applied with a strain rate of 0.21 mm/s at each test point. This strain rate corresponds to a loading frequency of 0.1 Hz. In other studies, the need to analyze the mechanical response of bovine articular cartilage at physiological stress levels [26] and to study the enzymatic degradation under dynamic unconfined compression loading [27] have been reported. In addition, some works have reported that

frequencies ranging from 0.01 to 2 Hz kept the majority of interstitial fluid inside the cartilage, which reproduces the phenomenon created by the real physiological frequencies in a human body [28-32]. Thus, the value used in the present work reproduce physiological cyclic loading, as it was done in previous studies.

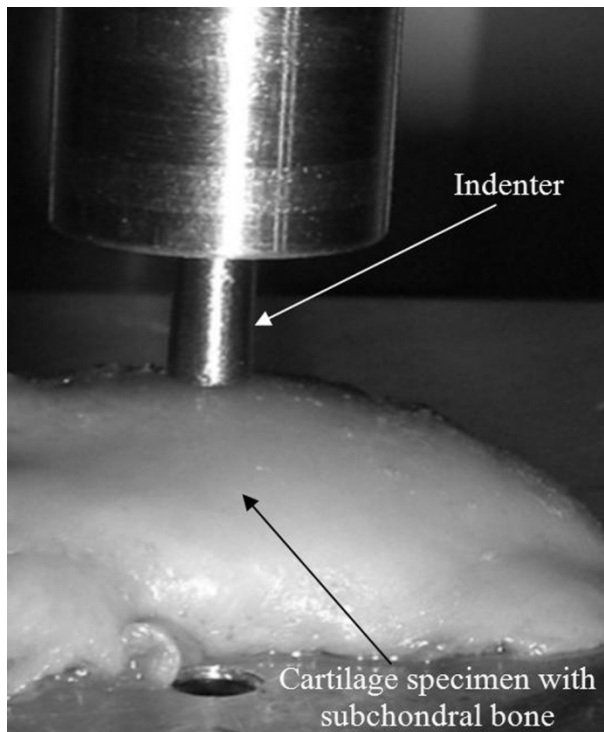


Figure 3. Cartilage specimen of femoral compartment for indentation test.

Furthermore, test runs were performed at the same points for all specimens and repeatability of cartilage response was observed. Force, time and displacement parameters were recorded during each test run.

#### 2.4 Relaxation test

Cartilage response to relaxation over time was obtained using the same 3 mm plane-ended cylindrical indenter as it was done in the indentation test. Specimens were fixed in a platform where they can be carefully adjusted so the cartilage surface is just in contact and perpendicular to the longitudinal axis of the indenter. A displacement of 1 mm in the axial direction was applied to each test point of the

cartilage specimen mentioned above (see Figure 2) and force and relaxation time were recorded during fifty seconds followed by cartilage unloading. The specimens were hydrated regularly with saline solution to prevent dehydration of the indentation surface and cells during testing time. Also, this reproduces the physiological normal state of cartilage hydration.

#### 2.5 Determining stiffness and relaxation modulus

Using the force values, time and displacement recorded in the indentation (see Figure 4) and the relaxation test, the following values were obtained:

- Percentage reduction of indentation force between cycles (%)
- Maximum mean stiffness (N/mm)
- Relaxation of the shear modulus (MPa)
- Relaxation of the bulk modulus (MPa)

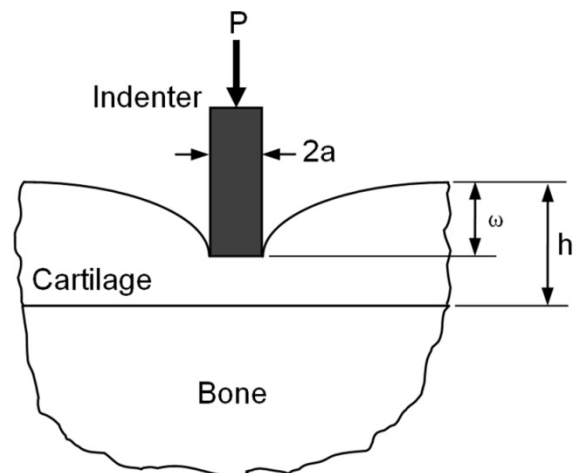


Figure 4. Schematic indentation test in cartilage with subchondral bone.

The resistance of an elastic body to deformation by an applied force is known as stiffness. Stiffness values were obtained normalizing the force values recorded over time in the cyclic indentation test to the corresponding depth of indenter penetration. This procedure to compute the stiffness was followed in previous works reported by Thambyah A. et al. [12] and Lyyra T. et al. [23]. Also, the relaxation of the shear modulus was obtained linking the mathematical model for the instantaneous elastic modulus reported by Hayes et al. [24] with the well-

known isotropic relation between the shear modulus and the elastic modulus. Thus, the relaxation of the shear modulus can be determined by

$$G = \frac{P(1-\nu)}{4a\omega k} \quad (1)$$

where  $G$  = instantaneous shear modulus  
 $P$  = indentation force  
 $\nu$  = Poisson ratio  
 $a$  = radius of the indenter  
 $\omega$  = depth of indenter penetration  
 $k$  = scaling factor of Hayes et al. [24]

The Poisson ratio is approximately 0.45 for the cartilage considered as an incompressible material [21, 23, 25] and when the load is applied for a short period of time [33]. In addition, relaxation of the bulk modulus for the cartilage specimens can be estimated as

$$K = \frac{2G(1+\nu)}{3(1-2\nu)} \quad (2)$$

where  $K$  = instantaneous bulk modulus  
 $G$  = instantaneous shear modulus  
 $\nu$  = Poisson ratio

### 3. Results

Figure 5 shows the general behavior of the indentation force as function of time for all cartilage specimens, which decreases through cycles. In addition, the viscoelastic effect has been observed between the loading and unloading curves, where relaxation of the indentation force is presented. This effect in all cycles is related to the change of movement direction of the indenter, which last approximately 1.5 seconds where the indentation depth is 0.5 mm. Also, a nonlinear behavior is observed at the beginning and at the end of each cycle for all cartilage specimens.

The application of the second cycle of displacement (Figure 6) shows that the indentation force decreases for the nonlinear loading curve as well as in the unloading curve. Also, the maximum

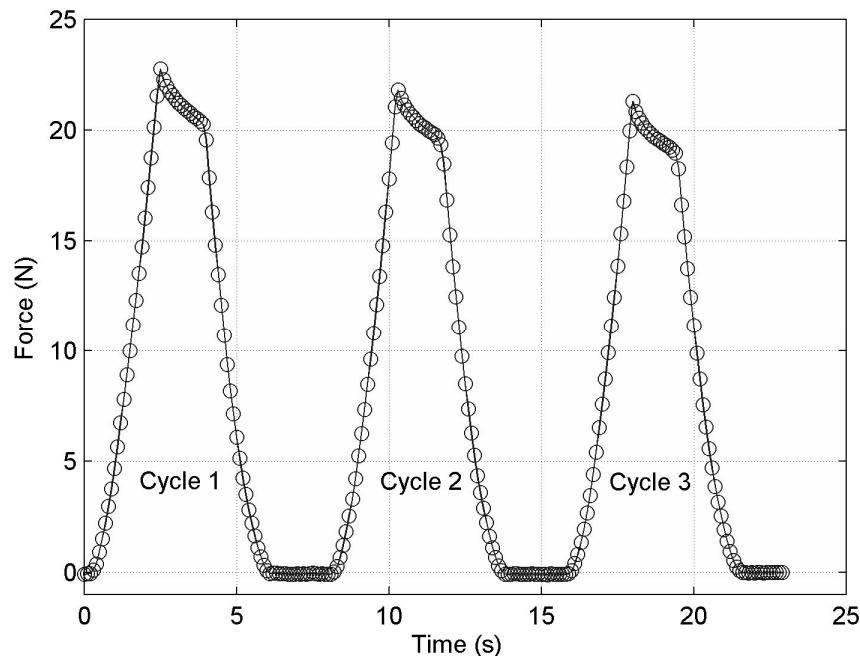


Figure 5. General behavior of the indentation force as function of time for specimens from femoral articular cartilage under unicompartmental osteoarthritis. Three consecutive cycles applied to the specimens are shown.

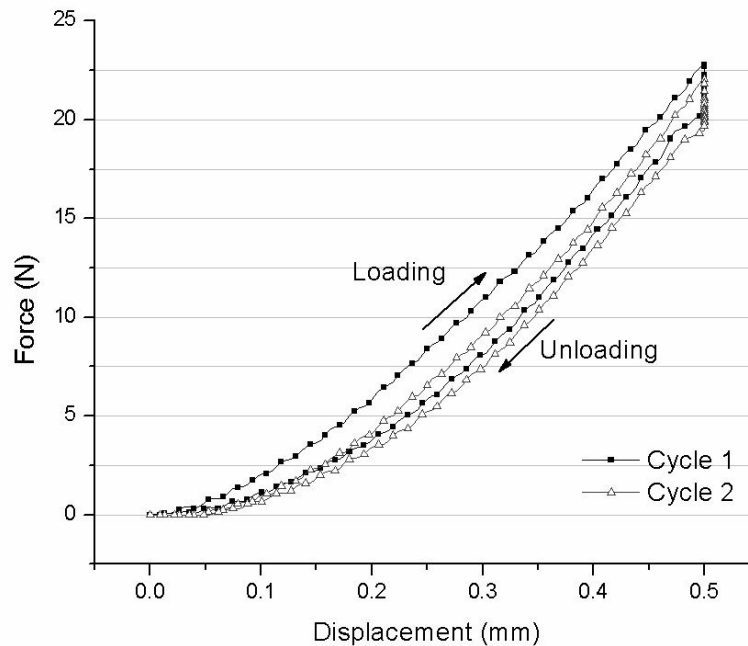


Figure 6. Indentation force behavior versus displacement for cycles 1-2 in one specimen of articular cartilage under unicompartamental osteoarthritis.

indentation force to achieve the final displacement of 0.5mm in cycle 2 decreased in relation with the maximum indentation force recorded in cycle 1. This behavior was presented in cycle 2 for all cartilage specimens tested in the present work.

The same behavior of the indentation force is observed for the third cycle of displacement (see Figure 7) since the maximum indentation force decreases in the loading and unloading curves between consecutive cycles. For this comparison, the percentage decrease of the maximum indentation force is less to that obtained with the previous cycles 1-2.

In order to analyze the decrease of the maximum indentation force between cycles 1-2 and cycles 2-3, the percentage decrease is computed for all cases. This value is observed for the different test points, as shown in Figures 8 and 9.

The MP point presented the maximum force decrease through cycles 1-2 (see Figure 8) while

the CP, AP and LP points presented similar mean values of force decrease.

For the second and third cycles, the MP point presented the maximum force decrease as it was also shown between the first and second cycles; however, in this case, the CP, AP, LP and PP points presented similar mean values of force decrease (see Figure 9).

Percentage values of the tested points have a general mean force decrease of  $6.75 \pm 0.71\%$  between cycle one and two while it is  $4.70 \pm 0.31\%$  between cycle two and three.

Table 1 shows the mean values and standard deviations (SD) of stiffness magnitudes obtained in the different test points of the cartilage in the lateral femoral compartment in each cycle. Based on these values, the cartilage stiffness increases between one and two cycles; however, it has a minor change between two and three cycles. The maximum stiffness occurs at point MP while the LP point has the minimum stiffness value in all cycles.

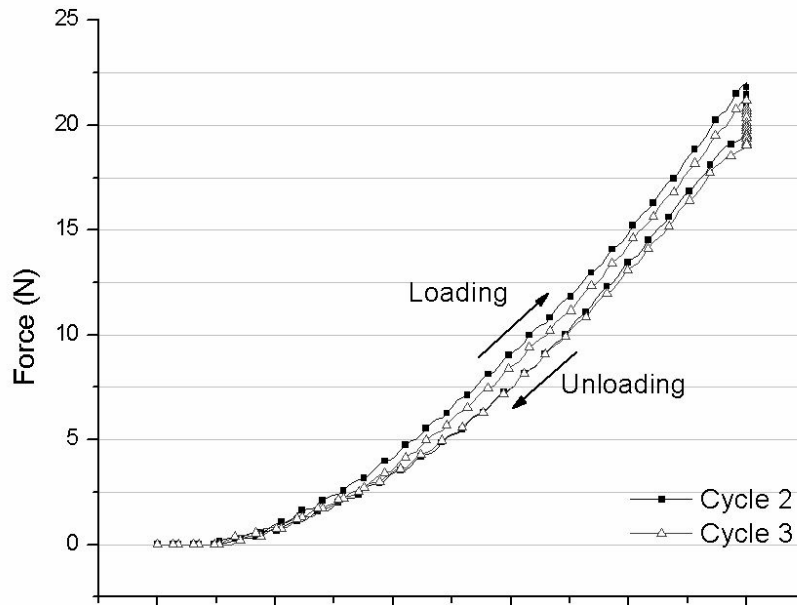


Figure 7. Indentation force behavior versus displacement of the indenter for cycles 2-3 in one specimen of articular cartilage under unicompartmental osteoarthritis.

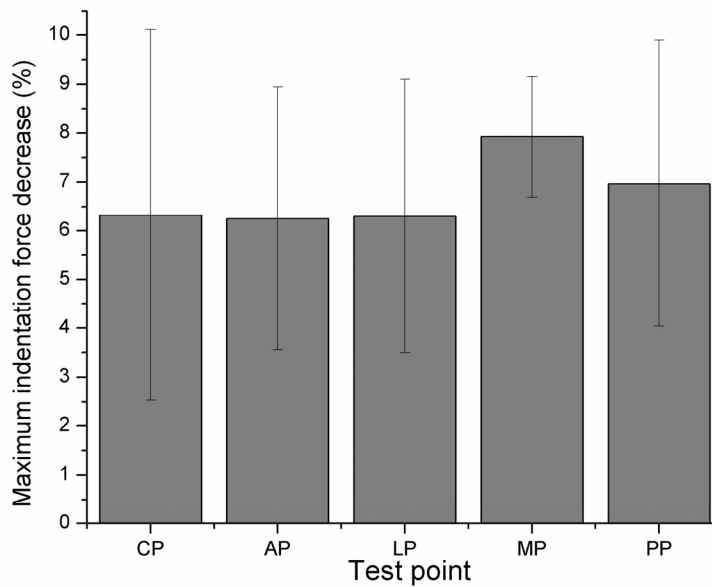


Figure 8. Percentage decrease in the maximum indentation force between cycles 1-2 for all test point in the femoral specimens of articular cartilage under unicompartmental osteoarthritis.

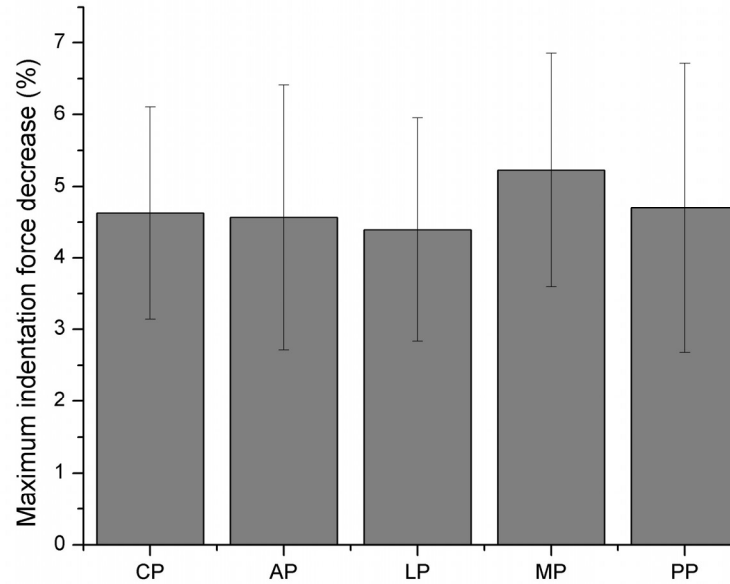


Figure 9. Percentage decrease in the maximum indentation force between cycles 2-3 for all test point in the femoral specimens of articular cartilage under unicompartmental osteoarthritis.

Test point	(N=7)	Cycle 1	Cycle 2	Cycle 3
CP	Mean	58.32	59.97	58.51
	SD	35.16	32.67	33.01
AP	Mean	47.27	48.99	49.91
	SD	23.45	26.91	28.81
LP	Mean	43.16	44.46	44.04
	SD	21.6	21.62	22.07
MP	Mean	80.37	83.34	82.44
	SD	34.25	38.32	39.46
PP	Mean	50.01	51.79	52.16
	SD	21.28	24.06	23.32

Table 1. Results of indentation cyclic testing for cartilage in unicompartmental osteoarthritis cases (Stiffness, N/mm).



Relaxation curves at each test point were obtained for all compartments and mean values are shown in Figure 10. The relaxation test showed a viscoelastic nonlinear behavior for the articular cartilage of the knee (see Figure 10).

#### 4. Discussion

The indentation force decreased in the cartilage specimens through the increase of the cycles. It can be related to the viscoelastic and biphasic behavior of cartilage which causes that the recovery is not instantaneous and the fluid flow in the cartilage is present in the indentation region [34, 35]. Thus, between consecutive cycles there is no time for total recovery and there is an initial deformation after the first cycle. The fluid flow has an important role in the mechanical behavior of the tissue. For instance, mechanical compression of cartilage causes a rapid pressurization of the fluid in the tissue, which in turn supports the load. This pressurization allows the longevity of cartilage under repeated compression since loading is

supported by fluid instead of a solid-solid interaction [36, 37]. Time-dependent changes occur in the fluid movement due to the fact that the fluid redistributes within the tissue, which contributes to the viscoelastic properties of the tissue. Due to the fluid pressure decrease over time, the solid fraction of the matrix suffers a higher load, giving rise to creep and stress relaxation behaviors [38]. Thus, the increase of cartilage stiffness (see Table 1) can be related with the loss of fluid pressure and fluid movement, which causes a higher load in the solid fraction of the matrix in the second and third cycle.

In addition, the effect of the fluid flow over the cartilage behavior is observed in the curves of the indentation force versus displacement (see Figs. 6 and 7) since the differences between the first and second cycle are notorious with mean decrease of  $6.75 \pm 0.71\%$  for the maximum indentation force; however, Figure 7 shows a decrease in the difference between the curves for the second and third cycle with a mean of  $4.70 \pm 0.31\%$  for maximum indentation force. It can be attributed to

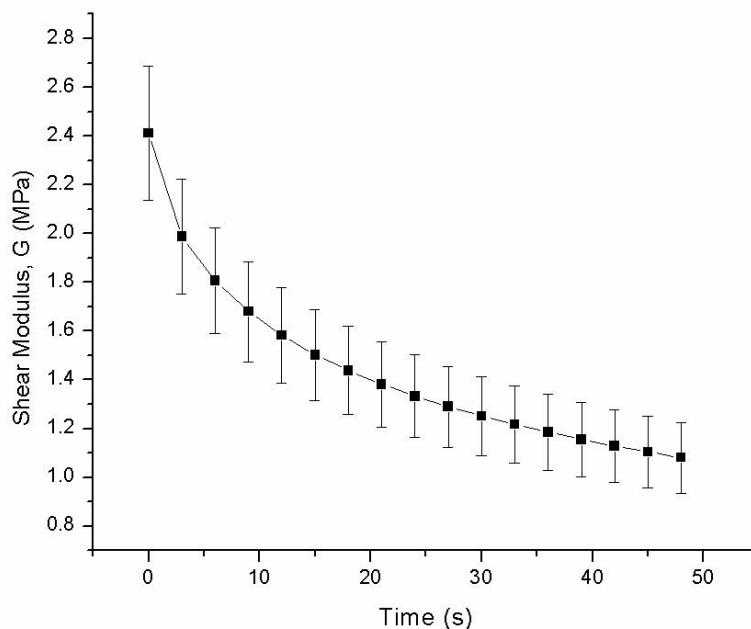


Figure 10. Relaxation shear modulus versus time for femoral knee cartilage with no visual damage in unicompartmental osteoarthritis cases.

the load supported by the solid fraction of the matrix. For this case, the fluid flow between the second and third cycle is less than the fluid flow between the first and second cycle.

Moreover, the percentage decrease in force is preserved between the different specimens and analyzed points (see Figures 8 and 9). This implies a common viscoelastic biomechanical behavior of cartilage specimens with no visual damage in knees with unicompartmental osteoarthritis.

In addition, we obtained larger values of stiffness for points AP, CP, PP and MP, which correspond to the displacement line of the kinematic axis of flexion [39] and areas of cartilage-cartilage contact [37] and load in the knee [40]. Nevertheless, the LP point corresponds to the lowest load in the knee. Also, the cartilage stiffness values (see Table 1) are larger in magnitude to those found for healthy cartilage in previous studies [12, 23].

Moreover, the relaxation test showed the nonlinear viscoelastic cartilage behavior over time. The maximum mean value obtained for the shear modulus in this test for a Mankin score 3 for all specimens was  $2.42 \pm 0.27$  MPa. This value is between the range of 1.6 to 6.4 MPa reported in human femoral compartments with Mankin score from 1 to 7 [41-42]. Also, mean values of the shear modulus in human cartilage of 3.34 MPa in the lateral compartment and 3.67 MPa in the medial compartment for Mankin scores of 4 and 4.5, respectively, have been reported [43]. Finally, the relaxation bulk modulus of the cartilage specimens (see Figure 11) has a nonlinear behavior similar to that obtained in the relaxation curve of the shear modulus. This is attributed to the consideration of the Hayes' isotropic model [24], which produces a linear relationship between the shear modulus and the bulk modulus.

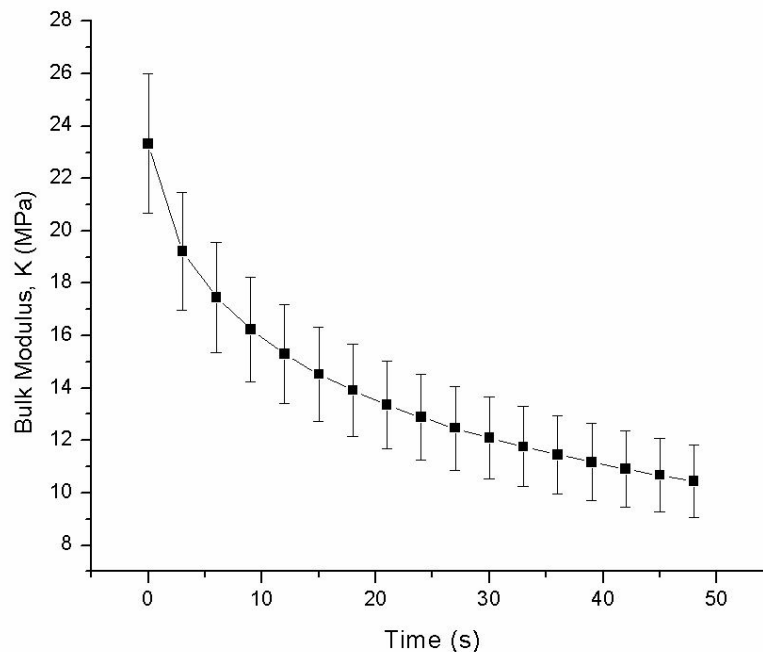


Figure 11. Relaxation bulk modulus versus time for femoral knee cartilage with no visual damage in unicompartmental osteoarthritis cases.

## 5. Conclusion

We showed that femoral cartilage with no visual damage in unicompartmental osteoarthritis cases preserves a dynamic nonlinear viscoelastic behavior. The cartilage specimens presented relaxation and delay in recovery. A common percentage decrease in the indentation force between cartilage specimens was observed. Also, the stiffness values of cartilage specimens through cycles showed that the cartilage stiffness increases between the first and second cycle; however, it has a minor change between the second and third cycle.

Our work provides experimental values of indentation force and stiffness through cycles and relaxation curves for the shear modulus and the bulk modulus over time. These experimental values can be used for validation of numerical material models to reproduce a more real cartilage behavior than those currently used in computer cartilage models for the study of UOA and unicompartmental knee arthroplasty. Also, these values allow us to know the stiffness requirements for the design of unicompartmental prosthesis in cases of UOA.

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