Measurement of Cartilage Deformation in Intact Knee Joints under Compressive Loading

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Paper History:

Received: 12th July 2021

Revised: 1st Dec. 2021

Accepted: 19th March 2022

Abstract

Many joints in the body depend on cartilage for their mechanical function. Since cartilage lacks the ability to self-heal when injured, treatments and replacements for damaged cartilage have been created in recent decades. The mechanical tests had an important role in the treatment and designing of the replaced cartilage. There are two types of cartilages in the knees: fibrocartilage (the meniscus, it is a special type of cartilage) and hyaline cartilage. Its mechanical properties are important because structural failure of cartilage is closely related with joint disorders. This study aimed to determine the stress-strain curve to give broader understanding of the material's properties. The results of this study could help to develop computational models for evaluating mechanics of knee joint, predicting possible failure locations and disease progression in joints.

The study involved two specimens taken from bovine, the first was the articular cartilage with subchondral bone and the second was the meniscus cartilage each one loaded on a compressive testing machine to compute the displacement, and the force applied, enabling the calculation of the stress-strain curve of the material.

Specimen failure occurred in the articular cartilage surface at a force break of 73.8N and get force peak about 87.2 N. The meniscus cartilage failure had occurred at a force break of 29.2 N and get force peak about 34.9 N.

Keywords: Articular Cartilage, Meniscus Cartilage, Compressive Test, Mechanical Characteristics, Failure, Force Break.

قياس تشوه الغضروف في مفاصل الركبة السليمة باستخدام فحص انضغاط العينة

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الخلاصة:

تعتمد العديد من مفاصل الجسم على الغضروف في الوظيفة الميكانيكية. نظرًا لأن الغضروف يفتقر إلى القدرة على الشفاء الذاتي عند الإصابة، فقد تم إنشاء علاجات واستبدال للغضروف التالف في العقود الأخيرة. كان للاختبارات الميكانيكية دور مهم في علاج وتصميم الغضروف المستبدل. حيث يوجد نوعان من الغضاريف في مفصل الركبة: الغضروف الهلالي (الغضروف المفصلي، وهو نوع خاص من الغضاريف) والغضاريف التي تغطي رؤوس العظام الموجودة في مفصل الركبة. تعتبر خواصه الميكانيكية مهمة لأن فشل بنية الغضروف يرتبط ارتباطًا وثيقًا باضطرابات المفاصل. هدفت هذه الدراسة إلى تحديد منحنى الإجهاد والانفعال لإعطاء فهم أوسع لخصائص المادة. قد تعمل المعلومات المكتسبة من هذه الدراسة أيضًا على تحسين النماذج الحسابية المستخدمة لتقييم مفصل الركبة ميكانيكيا وتقدير مواقع الفشل المحتملة وتطور المرض في المفاصل.

اشتملت الدراسة على عينتين من الغضاريف مأخوذة من مفصل الركبة في الأبقار، الأولى كانت عبارة عن غضروف على عظم والثانية عبارة عن غضروف هلالي مفصلي تم تحميل كل واحدة منها على آلة اختبار ضغط لحساب الإزاحة والقوة المطبقة، مما يتيح حساب منحنى الاجهاد والازاحة للمادة، وذلك لبيان مدى استجابة المادة للإجهاد المسلط عليها.

حدث فشل العينة الاولى أولاً في سطح الغضروف بدون الوصول الى طبقة العظم عند قوة مقدارها ٧٣,٨ نيوتن والحصول على ذروة قوة حوالي ٨٧,٢ نيوتن. حدث فشل الغضروف المفصلي عند قوة مقدارها ٢٩,٢ نيوتن والحصول على ذروة القوة حوالي ٣٤,٩ نيوتن.

1. Introduction

Articular cartilage and meniscus cartilage play an important role in load bearing and load distribution, providing stability as well as provide a smooth gliding surface during movement of the knee joint. The tissue geometry, ultrastructure, and composition of articular cartilage and meniscus cartilage have a significant effect on their biomechanical functions [1]. Comparing with the articular cartilage, the meniscal fibrocartilage has a reduced water amount (60–70% vs. 68– 85%), lower proteoglycan amount (1–2% vs. 5–10% by mass) and elevated collagen amount (15–25% vs. 10–20% by mass) [2]. When researching responses to mechanical stimulation, many features of articular cartilage and the meniscus in the knee must be taken into account. Both of these tissues have been demonstrated to be susceptible to a wide range of damages, including vehicle accidents and sports-related injuries [3]. Although it has been illustrated that articular chondrocytes and meniscal fibrochondrocytes respond to the alteration in their mechanical environment in vivo, the mechanisms that regulate matrix and mechanical properties are unknown [4, 5]. Several in vitro experiments were performed to explore the effects of mechanical stimulation on articular cartilage and the meniscus cartilage due to the hard difficulties of studying the in vivo environment [6, 7, 8]. The aim of this research was to create a direct compression load and investigate the effects of the compression on the articular and meniscal cartilages.

1.1 Anatomy of knee cartilage

There are two types of cartilage in knee joint: fibrocartilage (Meniscus cartilage) and articular (hyaline) cartilage [9]. The joint surfaces at the ends of the bones covered with articular cartilage serves as a shock absorber, allowing the bones to move smoothly, as well as there are two fibrocartilaginous menisci, medial and lateral, are found between the medial and lateral femoral condyles and the tibia, which allow for changes in the shape of the articular surfaces as a result of activity [10]. The structural components of cartilage are collagen fibrils and proteoglycans, and water all sustain the loads that are exerted on it. The collagen
fibers in the cartilage not only gives stiffness and strength, but it also helps to regulate the swelling pressure of the contained proteoglycans, which offer compressive stiffness to the tissue. In the physiological condition, these trapped proteoglycans contain a negative electrical charge. The Donnan osmotic fluid pressure, which exerted by this fixed charge density, has a crucial action in maintaining cartilage hydration and determining the tissue's capability to support compressive loads [11].

1.2 Exposuring of joints to the mechanical forces

The loading transferred to the hip or knee joints during walking is affected by the walking cycle phase (swing/stance), walking speed, as well as the surface inclination (level/up/down) and quality (soft/hard). Maximum loads in the knee and hip joints occur during level walking after heel contact, or when the support from one foot to the other happens. Maximum hip joint forces are 3–4 times body weight (BW) in some situations when walking slowly (1.1 m/s) or regularly (1.5 m/s), and can reach 7 BW when walking quickly (2.0 m/s) [15]. The maximum tibio-femoral force in the knee joint is rather lower at 3 BW during regular level walking. The femoral condyles' summits endure heavy loads in the knee joint, while the menisci are a key weight-bearing structure in the tibia, carrying up to 50% of the exposed knee joint load. Due to increased joint laxity, meniscus injuries are known to change knee joint kinematics. The femoro-tibial contact area is reduced after meniscectomy, and static and dynamic local contact stresses are increased [16].

2. Material and method

2.1 The specimens

Intact knee joint were obtained from skeletally mature bovine, as seen in figure (1), aged around two years old. In quantitative tests, bovine tissue has uniform quality, which reduced specimen variability, agreeing with that of human articular cartilage [12]. They prepared as the following:

•**Preparing of Cartilage-on-Bone Specimen**

The specimen harvested from slaughtered animal and sunken in Ringer’s solution in order to avoid dryness. It stored in a plastic container and kept frozen at -40 ºC until use. Bovine specimens had thawed at room temperature to be prepared for the test. The freezing and thawing process have no effect on the articular cartilage’s mechanical properties [13]. As seen in figure (2), the specimen was measured by vernier caliper, it was 25.3 × 18.45 mm along its surface, was cut from the joints. The articular cartilage layer was 2 mm. The cartilage-on-bone samples were taken from the femural head's central area. Since it has a planned surface and considered as the center of the joint's contact region, this position was chosen.

Figure (1): Intact knee joint of bovine

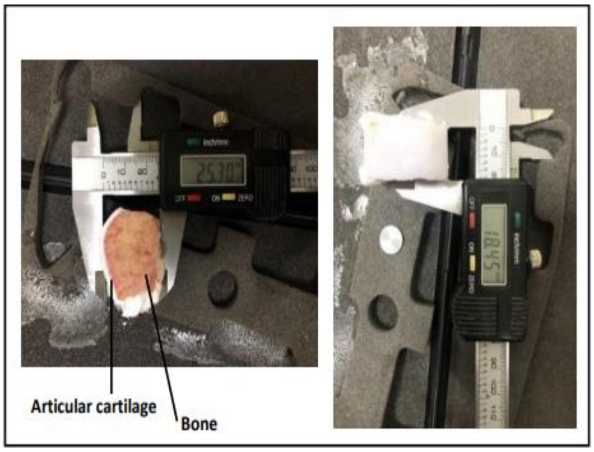

Figure (2): Measuring process for the Cartilage – on – bone specimen by Vernier caliper

• **Preparation of Meniscus Cartilage specimen**

The specimen harvested from slaughtered animal. The specimen was immersed in Ringer's solution, put in a covered plastic container and stored at −40 °C until use. Before testing, joints had thawed at room temperature. Rectangular shaped samples as seen in figure (3), their surface length measured approximately 10 × 6 mm, and 5 mm in depth, were cut from the joints by surgical scalpel with blade size 20A.

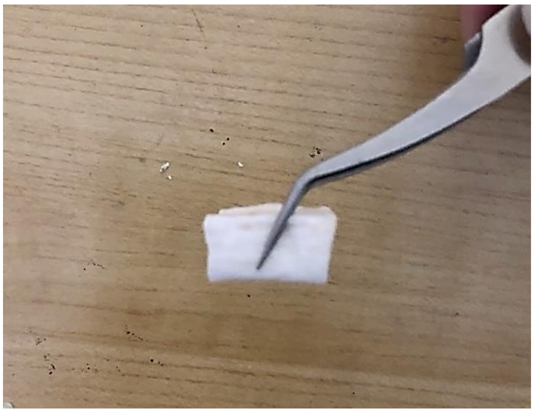

Figure (3): Meniscus cartilage specimen

2.2 Mechanical Loading

Specimens were tested using a "Universal Testing Machine (Testometric M500, 25 KN; Testometric Co, Rochdale, England", as shown in figure (4) that depended in previous study about artificial bone [14]. Load was applied by means of a flat, impermeable crosshead with 0.5 mm/min test speed. Tests performed without drying the specimens after taking them from Ringer's solution. The fresh cartilage-on-bone and meniscus cartilage specimen each one separately loaded, and a small load applied until the cartilage and upper crosshead made contact. So the compressive stress is distributed uniformly around the cartilage surface. The force applied gradually by automated computer control until the failure of the specimen occurred. Load-displacement data were recorded by computer using winTest analysis software.

3. Results and discussion

The articular cartilage –on – bone specimen loaded gradually as mentioned in figure (5). At the beginning of the test, the load is approximately 0 N until the upper crosshead fully contact the entire of the specimen surface as manifested from point A and B in the curve. The linear region from point B to C in the same curve means the load had increased with the increase of the deflection. This proportional relation ended at what is called as the yield point (at point C). Up to the yielding point, the material is not influenced by the applied stress and upon unloading, this is confirmed by [17]. The area up to the yield point is called the modulus of resilience, and the total area up to fracture is termed the modulus of toughness. The curve is ascending in force to reach the maximum value of the first layer of the specimen (articular cartilage) without fracture was 87.2 N (at point D). The result approved with the previous studies that got 40- 130 N of maximum force [18]. The maximum force will be evident providing its ultimate compressive strength value. After that point (D), the substance appears to strain (Deflection) soften, so that each raise of additional strain requires a smaller stress, for this reason the curve begin to descending after point D. As recognized in the curve, the failure had occurred at force break value 73.8 N (at point F). The test stopped at that point in order to get the failure of the articular cartilage only without bone.

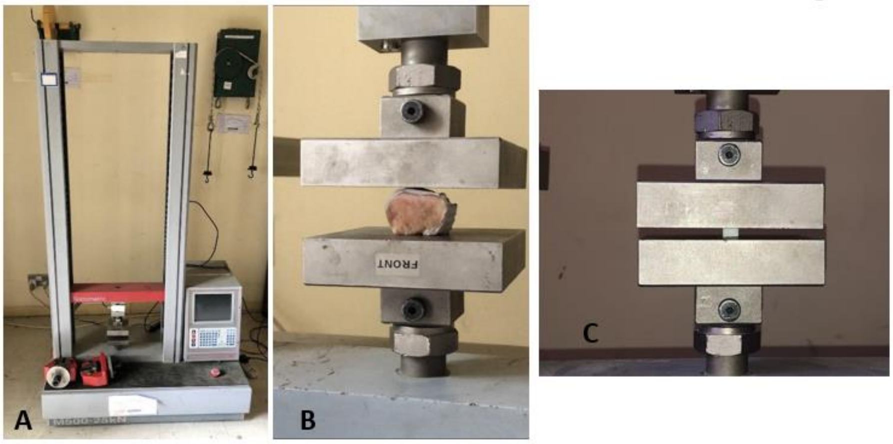

Figure (4): A-Universal Testing Machine. B- Cartilage –on –bone specimen under compressive load. C- Meniscus cartilage under compressive load.

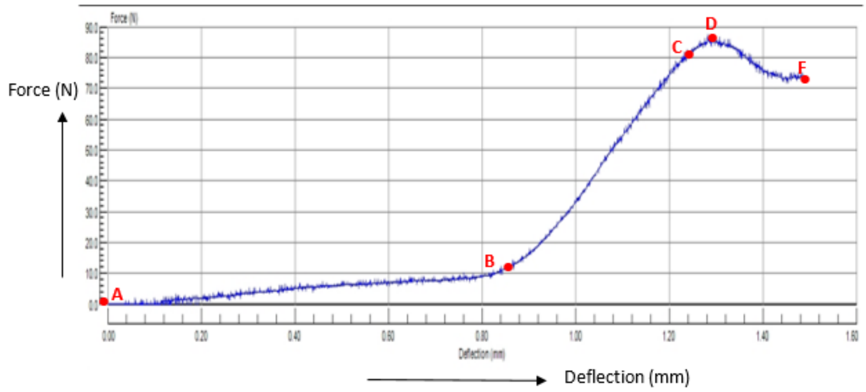

Figure (5): The force – deflection curve of articular cartilage specimen. (A) is the start point of the test, (B) to (C) is the linear region, (D) is the ultimate load, and (F) is the fracture point.

In figure (6), the load was 0 N (point A to B in the curve) until the specimen full contact with the upper crosshead as mentioned previously in articular cartilage testing. The meniscus cartilage specimen loaded gradually with speed 0.5mm/min to reach the ultimate strength at 34.9 N (at point D). The linear region of the meniscus is shorter than the articular cartilage that began from B to C in the curve. The linear region terminated and the yield point appeared at point C. The crack or failure of the specimen occurred at 29. 2 N (point F).

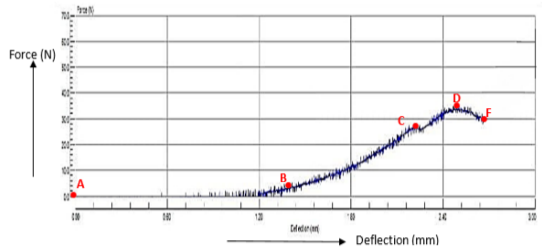

Figure (6): The force – deflection curve of meniscus cartilage specimen. (A) is the start point of the test, (B) to (C) is the linear region, (D) is the ultimate load, and (F) is the fracture point.

Yield and failure load observed in articular cartilage were greater than those of meniscus (81N and 73.8N), (28N and 29.2N) respectively. This results from collagen fiber straightening and different fiber recruitment in articular cartilage and meniscus [2]. A limited amount of proteoglycans and low compressive stiffness, to diminish the high stresses exerted on articular cartilage during loading, the superficial zone of articular cartilage might be exposed to relatively large strains. Since the linear area of the meniscus was slightly shorter than that of the articular cartilage, the articular cartilage was more resilient in the elastic region than the meniscus.

The stress-strain curve had been calculated by the force-deflection curve information by the following equation:

$$\sigma = \frac{F}{A_{\circ}} \qquad .. (1)$$

In which F is the applied force normal to the specimen surface, while $A_{\circ}$, means the cross-section area of the specimen. According to the international system of units (SI) engineering stress is expressed in megapascals (MPa).

In unconfined compression test, the Young's modulus (E) was calculated from the linear range of the stress-strain curve, assuming a homogeneous and isotropic material. All data was analyzed in Microsoft Office Excel, which allowed for the adjustment of curves that represent the tissue behavior according to the applied load. From these curves, it was possible to determine the mechanical properties of interest. The slope line had drawn on the curve to get the young's modulus from its equation as shown in figure (7). According to the slope equation, the young's modulus of articular cartilage was 0.3175 MPa. The results of the present study shows consistency with the study of Korhonen et al., 2002 [19].

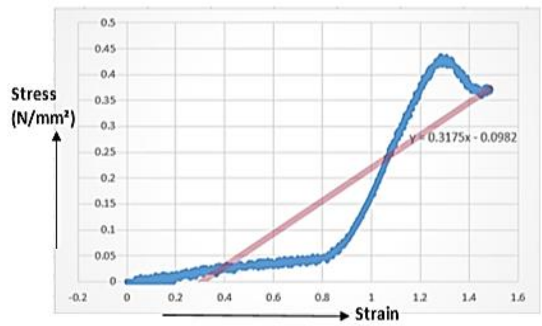

Figure (7): stress - strain curve of articular cartilage by Microsoft Office Excel

The young's modulus of meniscus cartilage was 0.2325 MPa that resulted from the equation of the red line in the stress- strain curve that shown in figure (8). This result deal with the finding of the previous study [20], which provided that the young's modulus ranged between 0.09 and 0.23 MPa.

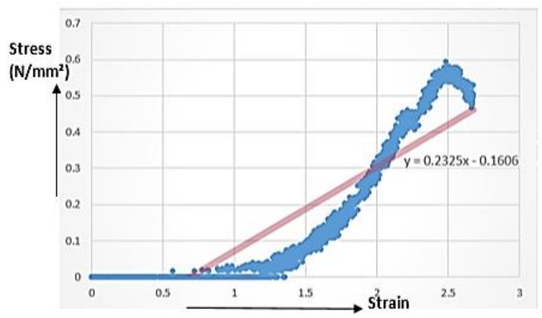

Figure (8): stress - strain curve of meniscus cartilage by Microsoft Office Excel

4. Conclusion

The ability of cartilage to perform its normal function under high compressive loads was evaluated by mechanical tests. Cartilage thickness has a major impact on its ability to equalize stresses between opposing bone surfaces, and marked thinning is one of the early symptoms of Osteoarthritis. The components of the cartilage such as the chondrocytes and the fibers were also influenced by the ultimate load that the specimen could bearing. The results of this study could help to develop computational models for evaluating mechanics of knee joint, predicting locations where failure may occur as well as disease progression in joints.

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