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DEVELOPMENT OF AN EXPERIMENTAL APPARATUS TO DETERMINE IMPACT RESPONSE OF ARTICULAR CARTILAGE

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ABSTRACT: *The articulations are subject to static and dynamic loads during daily living. Small impact forces can cause damage on articular surfaces as a result of repetitive impact stress. This paper describes a project for a drop tower to allow dynamic impact test in cartilage tissue aiming to understand the mechanics of the cartilage response to impact and seeking to obtain dynamic properties of cartilage, that are relevant for the description of contact-impact events. An instrumented drop tower was designed to enable controlled impact loads to be applied to small samples of biological materials. Different masses and weights can be applied to simulate different situations of impact severity. Quantitative information such as Young's modulus, coefficient of restitution, damping parameters and absorbed energy can be used in models for numerical and/or analytical calculations in contact-impact events.*

1 INTRODUCTION

Many studies have been developed to research properties of articular cartilage (AC) and its changes in the mechanical properties [1-5]. Measurements can be taken by applying impact load directly to the AC surface or indirectly by striking an exterior tissue such as the anterior patella and using pressure-sensitive film to characterize the peak stresses.

Methods of applying a direct impact include a free flying mass, a pendulum, and a drop tower. While hydraulic material testing machines are usually used to apply injurious compression, they are not able to apply a high enough rate of stress to deliver an impact load [2-4].

When cartilage tissue is subject to impact is usual the development of Osteoarthritis due to the death of the chondrocytes, changes in cartilage metabolism and alterations in the structural integrity of the AC that weakens its load-bearing function. AC is considered, mechanically, as a poroelastic material with a viscous interstitial fluid and an elastic matrix [6].

Experimental investigation of cartilage biomechanics during compression is typically performed by using confined or unconfined compression, or indentation. Unconfined and confined compression tests are commonly used to evaluate the Young's modulus and the aggregate modulus, respectively. It is well known that the composition and structure of AC vary through the depth of the tissue. As a consequence, the biomechanical parameters are expected to vary with depth.

During locomotion and sport activities cartilage is subjected to cyclic compressive loading, which causes progressive deformation. This is caused by the alteration of the fluid exudation and imbibition within its matrix, however, after a number of load cycles it reaches a steady state [3]. AC injuries frequently results in its degeneration. Some of main studies in thus field are presented in Table 1.

The description of contact-impact events requires the knowledge of the contact parameters for use in analytical or numerical calculations. In particular, for natural cartilage joints, the description of material behavior is a challenging task that includes several factors: static and dynamic stiffness; viscoelasticity; coefficient of restitution; damping properties; stiffness variation for degenerative diseases; impact energy absorption; morphology variation in contact-impact events. This paper deals with the development of experimental equipment, seeking to obtain dynamic properties of cartilage, that are relevant for the description of contact-impact events. A rigid and instrumented drop tower was designed to apply controlled impact loads to small samples of biological materials.

Tabela 1 Literature review on articular cartilage impact studies [3-6, 8-13]

Year	Authors	Work Description
1977	Repo and Finlay	Subjected the knee and hip to strain rates of 500 and 1000 s^{-1} if the load-bearing areas measure less than 500 mm^2, the femoral shaft may be fractured and it can cause chondrocyte death and fissures in AC.
1994	Obeid *et al.*	The “unaffected” cartilage from knees with unicompartmental osteoarthritis was thinner, softer and weaker than the control cartilage from corpse’s knees of similar age..
	Dahlberg *et al.*	Cartilage damage seems never properly to heal because collagen fragments, elevated levels of proteoglycans and stromelysin-1 have been found 15 years after injury. Cell death was also found at strain rates of 500 s^{-1}, for impact stresses of 20 MPa which produce a strain of 25%.
2000	Barber and Ciavarella	A study in a rabbit patellofemoral joint, using quasi-static approach, showed that Young’s Modulus of 2 MPa and Poisson’s ratio of 0.49 matched with those obtained from Finite Elements Method studies.
2001	Pandy	Cartilage is not usually included in numerical models because it not changes the transmitted forces by the joint; it only decrease the joint contact stresses by increasing the contact areas between the bones.
2007	Burgin and Aspden	Designed a drop tower to performed impact tests in biological tissues. The authors propose the calculation of coefficient of restitution from the strength/displacement curve obtained from the accelerometer data.
	Veteramo and Seedhom	Verified the effect of a single load in the structure and mechanical properties of AC. They determine that the mechanical properties of AC change at 25 MPa and it has a deformation rate of 1500 s^{-1}, resulting in an energy absorbed of 12.79 mJ/mm^3.
	Varga *et al.*	In addition to study the mechanical properties, studied the hysteresis curve (indicating the dissipation of kinetic energy) and characterize the flow of interstitial fluid, using experimental equipment like a pendulum.
2009	Boocock *et al.*	The running significantly alter the volume of the cartilage of the knee. These changes were similar independently of the sex in different cartilage compressive loads. They highlight the importance of create new models to study impact on the cartilage of the knee, to fully understand the contribution of biomechanical factors when subjected to knee joint to cyclic loading.

2 ARCHITECTURE AND DESIGN OF THE APPARATUS

The developed equipment is based on a drop-weight tower specifically designed for dynamic tests in soft tissues. It is required a rigid drop tower to ensure a free falling mass to impact on AC samples.

Research on the field concluded that the samples have a thickness of 0.5-2 mm and the duration of impact is in the order of milliseconds (about 6 ms). To be able to simulate more severe situations, such as car accidents, the impactor will be dropped from 1 m of height. Impact severity can be controlled by using impactors of different masses and various drop heights.

The stability of the apparatus is due to its simple design, a solid base plate, and an almost frictionless sliding guides, that allow to perform impact tests.

This apparatus consists in two linear guides with dimensions of 44x25x1225 supported by a solid and robust basis of steel with dimensions of 400x400x30. In order to control the friction on the linear guides, these will be composed by stainless steel with roller shaft.

The impactor will be also in stainless steel, with a weight of 500g. The dimension of the impactor was determined taking into account the mass of the stainless steel structure and the mass of the accelerometer. Two additional masses (250 and 500 g) can be inserted on the impactor to achieve larger impact masses of 750 and 1000 g.

The impactor will collide with the surface of the specimen, followed by a number of rebounds with decreasing velocities and heights. A system to stop the rebounds is still under study. However, the rebound of the impactor carries information on the material response to impact, important when analyzing the poroelastic parameters and dynamic mechanical performance [14].

The impactor will be dropped by a VEM034024SR electromagnetic system, and will impact on the sample in the basis falling only by gravity.

The sample holder has 45 mm in diameter and is made of stainless steel and acrylic, to allow visualization of the deformation of the sample through a high-speed camera.

The acceleration data can be recorded from an 8702B500 accelerometer (Kistler Instruments Ltd., Alton), made in titanium and with a weight of 7.1 g. This accelerometer is placed in the impactor and it has an acceleration limit of 5000 g, where g is the acceleration due to gravity, and this device was used before in other research works [4,5] in tests on AC, bone, and cartilage-on-bone samples.

The first experiments will be performed just for the calibration and validation of the system. Experimental tests in bovine articular cartilage will be performed to obtain the quantitative information required.

A 3D image of the apparatus designed is presented on Fig. 1. The detailed structure of the apparatus and its components are presented, respectively, in Fig. 2 and Table 2.

Fig. 1 Drop tower designed for dynamic impact in cartilage tissue

3 DETERMINATION OF MECHANICAL PROPERTIES OF THE ARTICULAR CARTILAGE

Quantitative information such as Young's modulus, coefficient of restitution, damping parameters and absorbed energy can be used in models for numerical and/or analytical calculations in contact-impact events.

The deceleration signal from the accelerometer can be integrated to obtain the velocity, which can then be integrated again to give the displacement.

The deformation δ of the sample can be obtained from the ratio of post impact thickness and the initial sample thickness. Acting forces (*F*) can be evaluated simply by using Newton's force law presented in Eq. 1.

$$F = mg \qquad (1)$$

where g is the acceleration of gravity and m is the mass of the impactor.

The peak dynamic modulus can be derived from the stress–strain curve by differentiating the stress–strain curve and finding the maximum. The energy of deformation can be found from the area under the loading curve (compression phase) by integrating to the maximum strain, and the energy released during restitution by integrating the unloading curve from this point back to zero strain [4].

The square of energetic coefficient of restitution may be obtained from the ratio between the energy released during restitution and the energy of deformation, as showed before in [5].

Quantitative information can also be obtained from the analysis of morphology before and after impact and video recording using high speed camera.

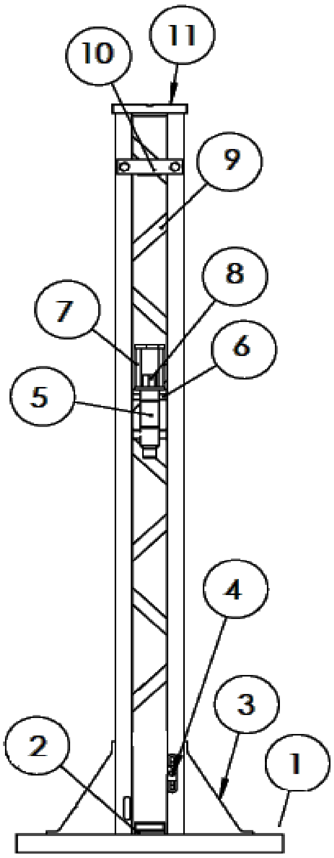

Fig. 2 Apparatus Components

Table 2 Components list

Item Number	Description
1	Base
2	Cartilage support
3	Base reinforce
4	Brake System
5	Impactor
6	Impactor support bearing
7	Electromagnetic linkage
8	Accelerometer adapter
9	Truss
10	Electromagnetic support
11	Upper guides support

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