A COMPARISON OF HEALTHY HUMAN AND SWINE JOINT CARTILAGE DYNAMIC COMPRESSION BEHAVIOUR IN MODES EMULATING JOINT FUNCTION

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SUMMARY
To determine whether possible implantable structures have mechanical properties close to native articular cartilage, the mechanical properties of the structures to be replaced have to be well known. However, fresh healthy human articular cartilage is not readily available. Therefore we tested whether swine cartilage could serve as a suitable substitute material. Functional stiffness of healthy swine and human joint cartilage specimens was determined and compared using two non-destructive methods: fast impact and slow sinusoidal mm-scale indentation. There was no difference in aggregate modulus between human and swine cartilage. However, the human specimen loss angle was ~35% lower in fast impact mode and ~12% higher in slow sinusoidal mode compared to swine cartilage. Thus, keeping possible loss angle differences in mind, swine specimens could serve as a standard of comparison for mechanical evaluation of e.g. engineered cartilage or synthetic repair materials.

INTRODUCTION
No synthetic implantable structures are yet available which come close matching the mechanical properties and durability of joint cartilage. The best relative measure of their success is to determine to what extent the resultant structures have mechanical properties which resemble those of healthy human joint cartilage. But this poses another problem--such human tissue is not readily available for ex-vivo use as a standard of comparison--i.e. to be subjected to the same mechanical tests as candidate synthetic structures, grafts, rejuvenated cartilage or engineered cartilage. In contrast, healthy animal joint cartilage is readily available for such purposes. However, one must then ascertain the extent to which such animal cartilage has the same mechanical properties as human cartilage.

The aims of this study were to (a) further develop the authors’ methods of measuring $E^*$ and $\delta$ of cartilage in both slow quasi-cyclic deformation and fast impact indentation, and (b) to determine and compare results for healthy swine specimens and healthy human cartilage. The overall goal was to establish whether swine specimens could serve as a standard of comparison for evaluating the extent to which joint cartilage replacement and repair strategies achieve cartilage-like mechanical behavior.

METHODS
Swine cartilage: Cylindrical osteochondral plugs of 7.6 mm in diameter were obtained from the knee joint of 10 nine month old swine. Plugs were harvested from the lateral patella (LP), the medial and lateral patellar groove (MPG & LPG) and from the medial and lateral condyles (MP & LP).

Human cartilage: Human articular knee cartilage tissues were collected from full-thickness biopsies of the lateral femoral condyle of 8 fresh human cadavers (median age: 57 years, range: 42-69) at the Department of pathology of the local University Hospital following informed consent by relatives and in accordance with the Local Ethical Committee. Tissue was only harvested from knees without macroscopical signs of degenerative arthritis.

Two different mm-scale indentation methods were used to determine stiffness properties (aggregate modulus $E^*$ and loss angle $\delta$). First, a fast impact (FI) micro-indentation was performed with an instrument developed at the Minsk institute of Physics [1]. Second, slow sinusoidal (SS) micro-indentation (1Hz) was performed with a Synergie 100 (MTS Systems, USA) equipped with a 2.5N loadcell (8432, Burster GmbH & Co, DE). Both methods provide dynamic force/displacement data. $E^*$ was calculated from the force-displacement data using Equation 1[1]:

$$E^* = \left(1 - \nu^2\right) \frac{3P\alpha_{\max}}{4\sqrt{\pi r}\alpha_{\max}}$$

Where $\nu$=Poisson’s ratio, $P$=force, $r$=indenter radius and $\alpha$=indentation depth. A $\nu$ of 0.44 was assumed. The $\delta$ was calculated from the phase shift between force and displacement data.

A one-sided Wilcoxon Rank Sum test was performed on stiffness data ($p<0.05$). Statistical analysis was performed using R (R Foundation for Statistical Computing, Austria).

RESULTS AND DISCUSSION
Strain rate dependency: The $E^*$ is significantly higher and $\delta$ is significantly lower in all specimens in FI-mode compared to SS-mode at all locations in the swine knee (Figure 1). Faster deformation rates result in higher $E^*$ and lower $\delta$, as previously shown by Park et al. [2] and others.
Anatomic location: In the swine knee, significant differences in the dynamic stiffness parameters were seen not only between the FI and SS modes, but also among various anatomic locations in the swine knee for each testing mode (Figure 1). It is already known that the stiffness of cartilage varies at different locations in human [3] and sheep [4] knees. Lyyra et al. [3] found the highest stiffness in the load bearing areas of the condyles, whereas we found the highest $E^*$ in the lateral patellar groove and the lowest $E^*$ on the lateral and the medial condyles. This difference might be due to a different loading pattern in swine knees compared to human knees.

Human versus swine cartilage: The resultant dynamic stiffness parameters of the LC human cartilage specimens are compared to the LC specimens of the swine in Figure 1. There was no difference in $E^*$ between human and swine cartilage. However, $\delta$ is $\sim$35% lower in FI-mode and $\sim$12% higher in SS-mode in human compared to swine cartilage. This difference might be due to a difference in composition of the cartilage. The question remains why $\delta$ for human cartilage is higher than for swine in FI but lower in SS-mode. In the FI-mode the indentation lasts less than 2 ms. At this loading rate and given the low permeability of healthy cartilage, water does not flow appreciably and there is little absorption of energy due to flow-related friction. Therefore, the energy loss measured might be mainly due to aggregate viscoelasticity of the cross-linked collagen fibers. In contrast, in the much slower SS-mode, significant perfusion of water in response to the applied load is indicated by the much higher loss angles. With these factors in mind, the results suggest that (a) cross linked collagen in human cartilage is more viscoelastic than in the swine, and (b) the proteoglycan matrix in human is less permeable than in the swine. The differences are not major ones, however. These differences might be due to the fact, that cartilage from different species is compared; on the other hand, the differences might be due to age difference. Swine cartilage from adolescent animals was compared to cartilage from adult to elderly humans.

CONCLUSIONS
This study shows that with some provisos, swine articular specimens could serve as a standard of comparison for evaluating e.g. engineered articular cartilage or entirely synthetic repair materials.

Our results also suggest that fast impact indentation tests are more valuable to differentiate between differences of cartilage dynamic stiffness parameters. Besides the modulus, loss angle is an important dynamic stiffness parameter of cartilage and should therefore be a part of every test set that defines the quality of cartilage or a cartilage repair material.

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REFERENCES