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Friction properties of a new silk fibroin scaffold for meniscal replacement

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ABSTRACT

The menisci protect the articular cartilage by reducing contact pressure in the knee. To restore their function after injury, a new silk fibroin replacement scaffold was developed. To elucidate its tribological properties, friction of the implant was tested against cartilage and glass, where the latter is typically used in tribological cartilage studies. The silk scaffold exhibited a friction coefficient against cartilage of 0.056, which is higher than meniscus against cartilage but in range of the requirements for meniscal replacements. Further, meniscus friction against glass was lower than cartilage against glass, which correlated with the surface lubricin content. Concluding, the tribological properties of the new material suggest a possible long-term chondroprotective function. In contrast, glass always produced high, non-physiological friction coefficients.

1. Introduction

The semilunar menisci are located between the femoral condyles and the tibial plateau of the knee joint [1–4]. They play a decisive role in load distribution by increasing the contact area between the incongruent femoral and tibial articular surfaces. Additionally, they are involved in secondary joint stabilisation, nutrient distribution and providing joint motion at low friction [3–5]. Loads of up to 3.5 times body weight are transferred through the knee joint during activities of daily life, whereby in general 45–70% of the total load is transmitted through the menisci [6,7]. In experiencing such high mechanical stress, the menisci are prone to injuries requiring surgical intervention in approximately 85% of cases [8]. The most frequent surgical therapy for meniscus injuries is a partial meniscectomy. However, various studies have shown that a partial meniscectomy determines the onset of cartilage degeneration, leading to osteoarthritis (OA) in the long term [9–11].

Removing meniscal tissue leads to a reduced contact area associated not only with an increased contact pressure but also with greater friction [3–5,10–12]. McCann et al. additionally identified fibrillation of the cartilage surfaces immediately after removal of meniscal tissue and wear of the articular cartilage [12]. Therefore, concepts for the restoration of meniscal function by implantable devices should comprise not only the ability to transmit loads but should also consider how to mimic the low friction provided by the native meniscus. Various biomaterials with different biomechanical properties have been developed to replace the injured meniscal tissue and restore its function [13,14]. Two resorbable scaffolds (CMI® by Ivy Sports Medicine GmbH, Actifit® by Orteq Ltd.) are currently available and in clinical practice. However, Sandmann et al. showed their lack of biomechanical stability in comparison to the native meniscus within an *in vitro* study [15]. Another non-resorbable scaffold for partial meniscal replacement based on silk fibroin (FibroFix™ Meniscus, Orthox Ltd., Abingdon, UK) was recently investigated in a sheep model, showing promising results regarding biocompatibility and the prevention of OA after 6 months [16]. However, no results are currently available predicting its long-term chondroprotective function. To maintain the chondroprotective properties of a meniscal scaffold over an extended period of time, its frictional behaviour is of major importance as a high friction coefficient leads to wear, which is associated with cartilage fibrillation.

In general, friction is defined as the resistance of motion between two surfaces that are in contact. According to Coulomb, the friction force F_R is equal to the product of the friction coefficient μ and normal force F_N. Therefore, the friction coefficient is a material property and could be calculated from the quotient of friction and normal force. However, within synovial joints, friction is much more complex. This is due to the biphasic viscoelastic nature of the opposing surfaces of the meniscus and articular cartilage lubricated by synovial fluid [17].

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Various studies investigated the frictional behaviour of articular cartilage [18–26]. Regarding the three lubrication modes transferred from mechanical friction analysis (i.e., fluid, boundary and mixed lubrication), numerous tribology theories were postulated to describe the remarkable frictional behaviour of articular cartilage [17,26–31]. Within these studies, it has been shown that the friction in synovial joints is multifactorial and several parameters, including applied normal load and strain, sliding speed, time and lubricant, influence the friction mode [23–26,31]. Furthermore, the opposing surface used to test friction characteristics naturally has a major effect on the friction coefficient. Glass, which was typically used in most cartilage friction studies [19,22,25,28,32], provides a smooth counter surface, but its use appears at least debatable in terms of its lack of physiological properties. Testing articular cartilage against glass leads to an increase in friction over time until an equilibrium is reached due to the biphasic, viscoelastic nature of cartilage [33]. This phenomenon is most likely attributable to interstitial fluid pressurisation within the articular cartilage [19,20,22,25,34]. It has been shown that the applied load is initially supported by the fluid phase of the biphasic cartilage, resulting in a very low friction coefficient. Under a persisting load, the load support is continuously transferred to the solid matrix, resulting in an increasing friction coefficient [22,34]. This phenomenon is typically observed in highly hydrated and biphasic tissue.

The above mentioned silk fibroin based scaffold for permanent meniscal replacement is processed into a porous matrix with a smooth surface [16]. Although its ultrastructure differs considerably from the native meniscus it showed promising results in a first *in vivo* trial in sheep [16]. Additionally, Parkes et al. demonstrated a cartilage-like friction response of silk protein hydrogels in articular cartilage repair [35]. Based on these findings, we hypothesised that the friction coefficient of the silk fibroin scaffold for meniscal replacement is comparable to physiologically articulating surfaces. We further hypothesised that glass as an opposing surface leads to higher friction coefficients not only for articular cartilage but also for meniscus and scaffold in comparison to those achieved when tested against cartilage.

2. Method

2.1. Study design

The frictional properties of the silk fibroin scaffold for meniscal replacement were determined in comparison to the physiologically articulating surfaces of meniscus and articular cartilage. Therefore, cylindrical samples were prepared from the silk fibroin scaffold as well as being retrieved from the meniscus and tibial cartilage of seven intact bovine knee joints (age: 3 months) (Fig. 1). Each cylindrical sample was first tested against a flat cartilage sample, which was also harvested

Fig. 2. Macroscopic image of the meniscal silk fibroin scaffold (FibroFix™, Orthox Ltd., Abdindon, UK).

from the bovine knee joints, using a *pin-on-plate* friction-testing device. During testing, the flat opposing surface slid cyclically against the cylindrical samples, while a constant normal load of 14.6 N was applied to them, resulting in a detectable friction force. All samples were stored overnight in phosphate-buffered saline (PBS) at 4 °C for recovery and tested against glass the next day to test the second hypothesis.

2.2. Detailed procedure

2.2.1. Sample preparation

The scaffold samples used in this study were manufactured by Orthox Ltd. and consisted of a biomaterial based on the protein, fibroin, extracted from silk fibres of the mulberry silk moth *Bombyx mori*, which was subsequently processed into a porous matrix (Fig. 2). Seven scaffold samples were retrieved from 6 flat sheets (height h_0=3.4 mm ± 0.6 mm) using a biopsy punch (ø=6 mm). Seven fresh intact bovine knee joints were ordered from a local butcher and stored at −20 °C. The day before testing, the joints were kept at 4 °C to thaw. Cylindrical meniscus samples (ø=6 mm) were punched out from the medial meniscus at the transition of the posterior horn and the *pars intermedia* perpendicular to the surface that was physiologically in contact with the femoral condyle. For later fixation in the friction testing apparatus, the cylindrical samples required parallel surfaces.

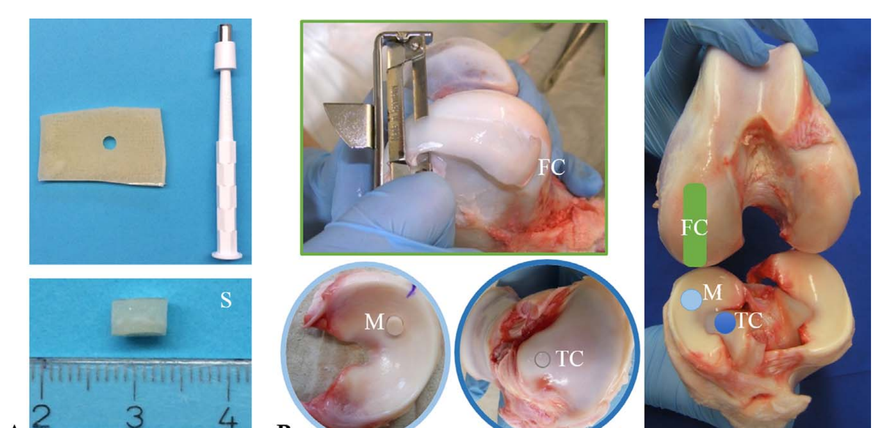

Fig. 1. Cylindrical samples were prepared from flat sheets of the silk fibroin scaffold (S) (a), as well as being retrieved from the meniscus (M) and tibial cartilage (TC) of bovine knee joints (b). Flat cartilage samples were taken from the femoral condyle (FC) serving as the opposing surface during friction testing (b).