A wear model to predict the damage of ACL implants

D. Maeztu Redin[a,b], J. Caroux[a,b], P.-Y. Rohan[c], H. Pillet[c], A. Cermolacce[d], J. Trnka[d], M. Manassero[d], V. Viateau[d] and L. Corté[a,b]

[a]Centre des Matériaux, MINES ParisTech, PSL University, Évry, France; [b]Molecular, Macromolecular Chemistry and Materials, ESPCI Paris, PSL University, Paris, France; [c]Institut de Biomécanique Humaine Georges-Charpak, Arts et Métiers, Paris, France; [d]École Nationale Vétérinaire d'Alfort, Laboratoire de Biologie, Bioingénierie et Bioimagerie Ostéo-Articulaire, Maisons-Alfort, France

1. Introduction

Anterior cruciate ligament (ACL) reconstruction is a surgical procedure with overall good outcomes (75%–97%) (Samitier et al. 2015). However, the ætiology of ACL reconstruction failure remains often unclear. While some causes are hard to predict—infection, improper immune response … —some mechanical causes could be prevented by adequate graft design and placement. Here we study how over-stretching, excessive twist, impingement, and wear of the implant with other structures like cartilage and bone affect implant damage. To address this, we used a sheep model—current standard for ACL preclinical trials— of arthroscopic ACL reconstruction We compared those damage predictors to *in-vivo* indicators of damage.

2. Methods

Seven sheep (20–41 months, healthy) underwent ACL reconstruction using tendon autografts. The limbs were explanted at three months after ligamentoplasty. For each specimen, biplanar radiographs were acquired using low-dose X-rays (EOS, EOS Imaging, Paris). Using a reconstruction algorithm (Azmy et al. 2010), 3D surface meshes of the femur and the tibia were obtained. The cadaveric sheep knee specimens were then tested in vitro using a motorised device and motion capture (Polaris®) to record knee kinematics in flexion-extension. Joint laxity was assessed via varus-valgus and tibial translation tests. Damage was characterised by necropsy observations (Outerbridge grading for cartilage damage; Outerbridge 1961) and ultimate tensile strength (UTS) of the graft (Guerard et al. 2014). The 3D meshes and kinematic data in the form of translation matrices were integrated into a 3D computer model of each knee (Figure 1). Correlations

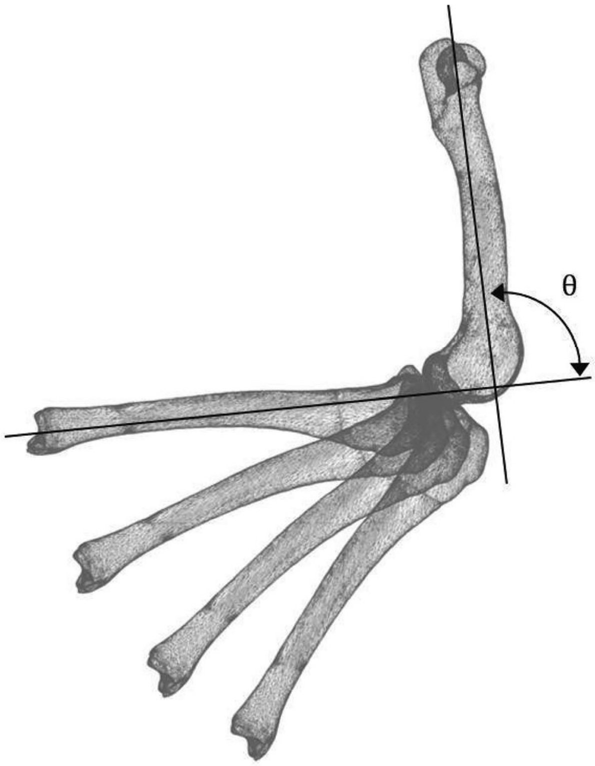

Figure 1. Reconstructed 3D images of femur and tibia showing knee flexion-extension kinematics of a limb; θ knee flexion angle.

(Pearson, r) between UTS and model variables (predictors) were studied.

3. Results and discussion

Laxity tests showed that operated joints were laxer than their respective, non-operated contralateral joints. Pull-out force of grafts was 80% lower in average than at the non-operated ACL of the contralateral limbs ($p < 0.001$). We aimed to identify a damage criterion that explained these differences in mechanical resistance. From the digital model, we computed the maximum values of strain, angle of twist and impingement volume underwent by the graft during a knee flexion-extension movement. When compared to UTS, none of these variables explained the resistance of the grafts in vivo ($r = 0.167$, $p = 0.721$; $r = -0.289$, $p = 0.530$ and $r = -0.219$, $p = 0.638$ respectively). Using kinematic data, a wear model based on Archard-Reye model (Archard 1953) was proposed to assess local wear accumulated on the graft during a knee flexion cycle. In this model, wear—progressive loss of material—is proportional tothe work done by the friction forces. Accordingly, the relative displacements between graft

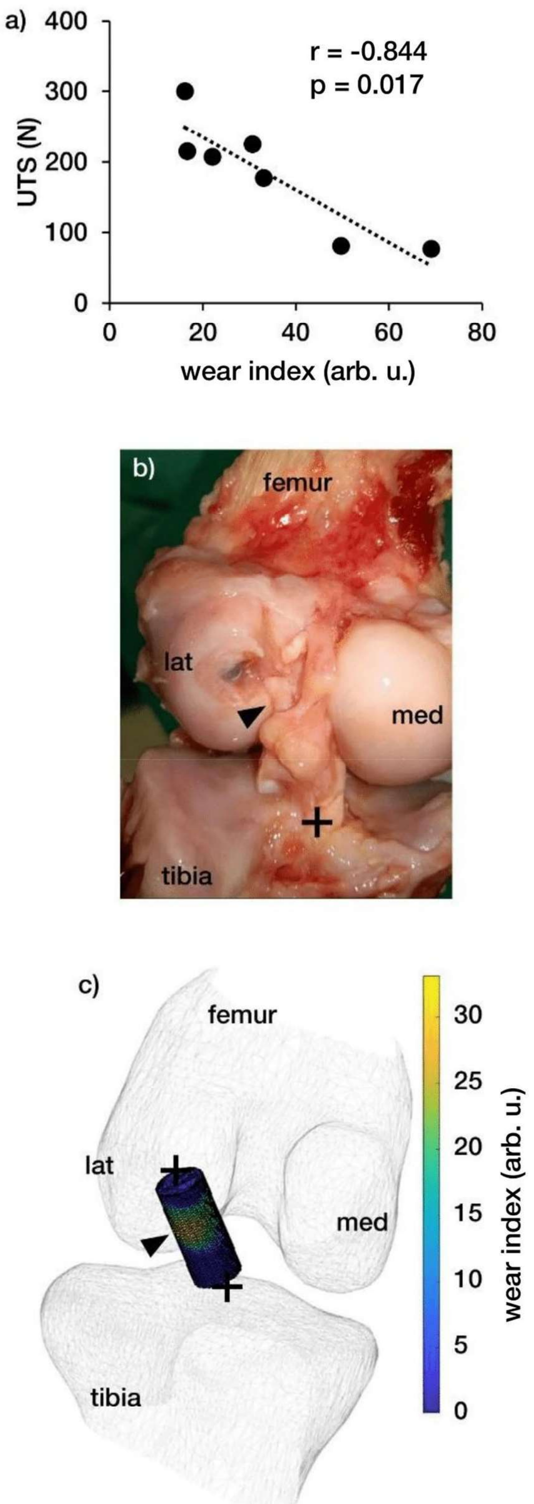

Figure 2. (left): a) Scatterplot of UTS and wear index. Both variables are negatively correlated; dashed line gives best linear fit. b) Necropsy observation of an operated knee at 3 months after surgery. Black arrow indicates damage on the graft. Crosses show the location of the femoral and tibial insertion points. c) Corresponding prediction of local wear on the graft for the same knee. Black arrow indicates the location of the maximum wear index on the reconstructed ACL.

and bones; together with an approximation of the normal force were used to compute an index scaling like the local work of friction forces accumulated on each point of the graft surface during a full flexion-extension movement. The normal force was approximated by the penetration depth, following Hertz's contact theory. The maximum value of this index attained on each graft (denoted as wear index) showed a strong negative correlation with UTS ($r = -0.844$, $p = 0.017$) and explained the differences among specimens (Figure 2a). Moreover, the distribution of local wear on the graft surface was compared to necropsy observations, where damage zones were consistent with the predictions (Figure 2b and c).

4. Conclusions

This study shows that impingement alone is not enough to assess graft damage of reconstructed ACL. It is necessary to account for kinematics, in particular the relative displacements of the graft with adjacent structures. We showed how this wear assessment can be done through a geometrical description and a simplified Archard model, which successfully captured graft damage after three months of implantation. This model provides a local distribution of wear at the graft surface and can be used to localise areas of potential damage. Its direct application to sheep anatomy offers a way to increase efficiency of preclinical testing and an implementation could be envisioned for surgery planning of human ACL reconstruction.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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