Artificial Anterior Cruciate Ligament (ACL) Reconstruction for more Natural Knee Kinematics

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AIMS

- To define the design criteria of an artificial ACL which could reproduce the non-linear load-elongation characteristics of the native ACL
- To investigate the mechanical behaviour of a novel ACL reconstruction design

INTRODUCTION

Kinematic and survivorship studies on ACL deficient knees have emphasised the importance of preserving and/or reconstructing the ACL [1]. The unique structure of the ACL enables a non-linear response to force at different flexion angles, this is thought to be a key element in providing normal knee kinematics (Fig 1).

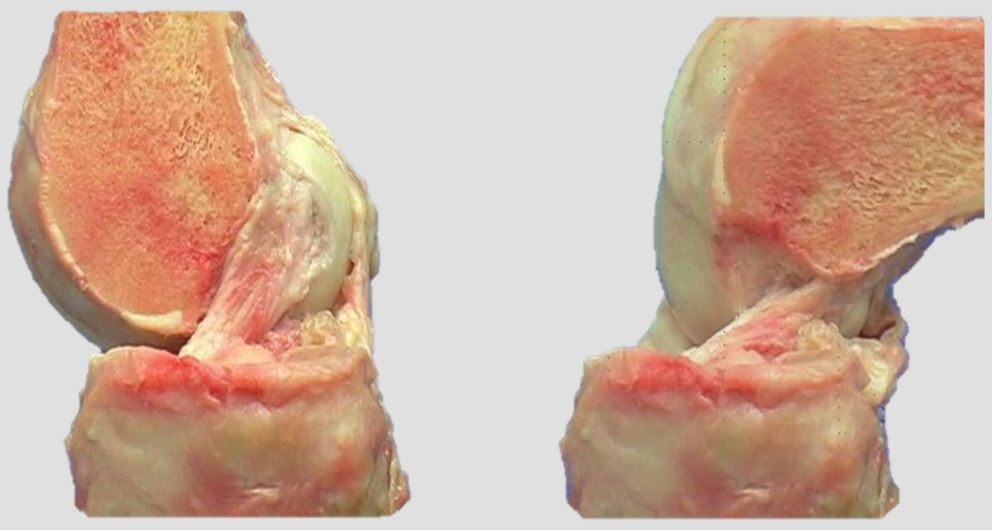


Fig 1. Sagittal view of the ACL at full extension (left) and 90 ° of flexion (right) [2]

Current synthetic ACL reconstruction grafts have shown poor long-term results, mainly due to wear, creep, fatigue and mechanical failure. None of the synthetic and biological grafts used for the ACL reconstruction have been able to replicate the normal mechanical behaviour of the ACL and prevent degenerative disease progression such as osteoarthritis.

MATERIALS & METHODS

The desired non-linear load-elongation characteristics of the synthetic ACL were defined based upon the *in vitro* and *in vivo* characteristics of the native ACL [3]. The design selected for the artificial ACL consisted of a metallic elastic system and a polymeric cord; whether this system could simulate the non-linear behaviour was examined, and mechanical tests were performed to assess the feasibility of long-term implantation. Suitable materials for the ACL reconstruction design (CoCrMo alloy and UHMWPE fibres (Fig 2) were identified based on their biocompatibility, strength, strain, creep and fatigue properties (Fig 3).

Fig 2. Braided construct of UHMWPE fibre [3]

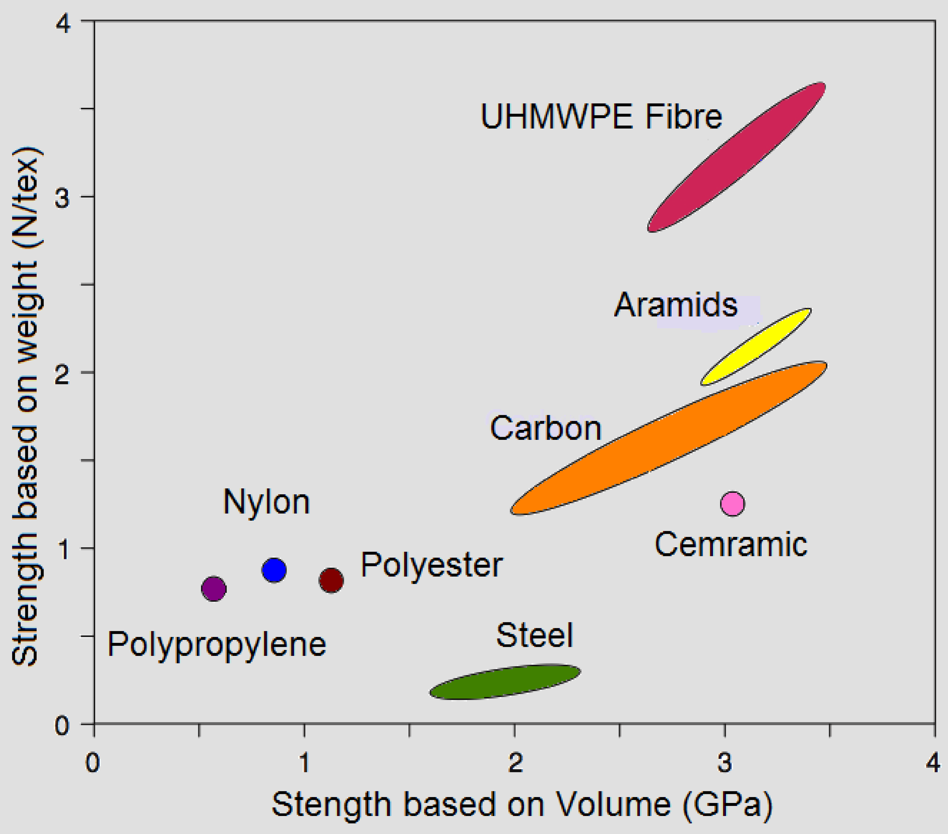


Fig 3. Strength of different fibres based on their weight and volume [4]

The effect of humidity, temperature and strain rate on the mechanical properties of UHMWPE loops was investigated. Cyclic fatigue tests were performed on UHMWPE loops for up to 6.4 million cycles at 1 Hz under 40-400 N load in simulated body conditions.

In order to investigate whether the system could reproduce the non-linear properties, finite element modelling was used. The accuracy of different plasticity models to predict the UHMWPE loop under cyclic loading were examined to identify the most suitable material modelling approach; the loading- unloading uniaxial cyclic test was virtually simulated on finite element models using ABAQUS software (version 6.9- Simulia- RI, USA).

The prototype ACL design was tested on three cadaver knees; the restoration of joint stability was quantified using a KT1000 arthrometer. The synthetic ACL design was implanted with/ and without total knee replacement (TKR). For each knee, anterior tibial translation was measured for; the intact healthy knee with/without surgical exposure, after ACL removal (ACLD), after ACL reconstruction (ACLR), after TKR (ACLD TKR), and after TKR with reconstruction (ACLR TKR).

RESULTS

The native ACL has been shown to have a non-linear stiffness (Fig 4) with a low resistance to the initial load (~30 Nmm^{-1}) and increased stiffness under higher load (~110 Nmm^{-1}). When the stiffness of the metallic elastic system and the polymeric cord were examined, the combination of materials were shown to be able to potentially recreate these mechanical properties (Fig 5).

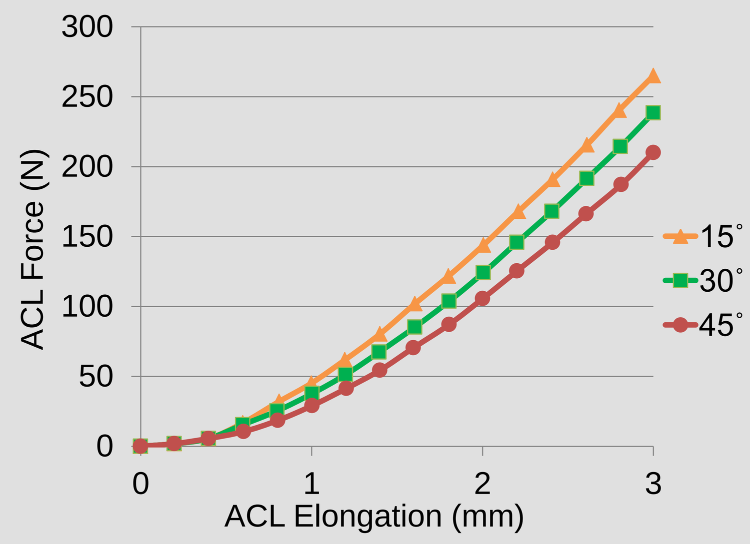


Fig 4. *In vitro* non-linear load-elongation behaviour of the ACL at different flexion angles [5]

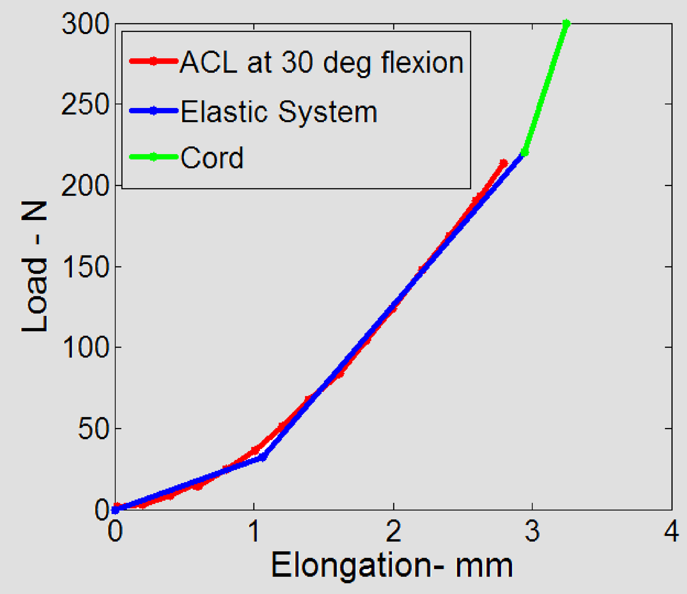


Fig 5. Replicating non-linear behaviour of the ACL by using 2 elastic systems and a cord

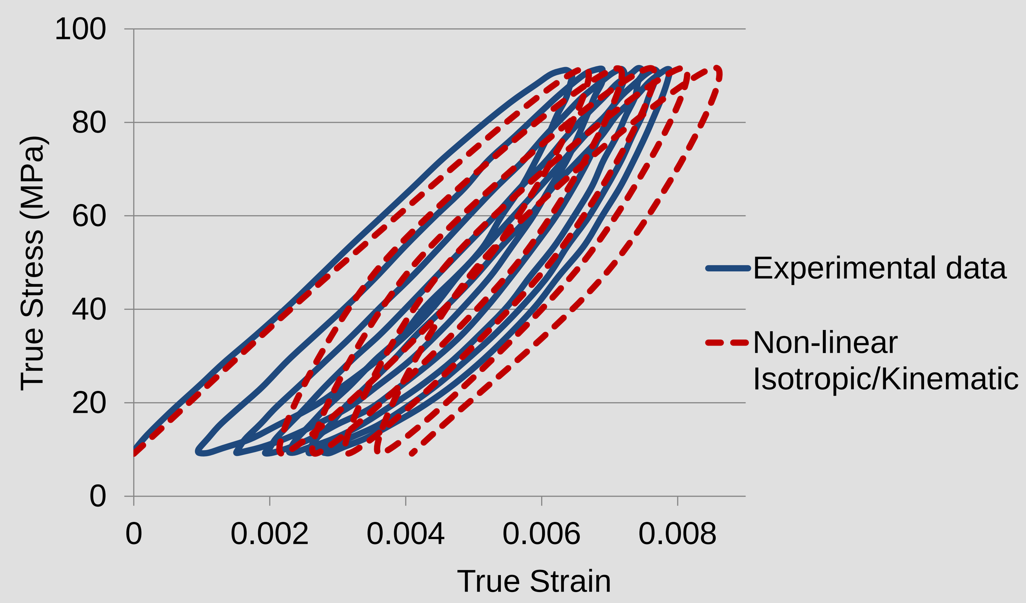
Body temperature did not have a significant effect on the mechanical properties of the loop specimens, whereas, humidity significantly reduced the tensile strength. Increasing strain rate increased the stiffness of the UHMWPE cord. Results of the cyclic fatigue test showed that cord reached a steady state before 250 cycles and the specimen passed 6.4M cycles without mechanical failure.

The non-linear kinematic hardening model best predicted the cyclic behaviour of the UHMWPE loop (Fig 6), and was able to predict the strain to an accuracy of 24.2%. The optimised model parameters are summarised in Table 1. The isotropic and linear kinematic hardening models over-predicted the residual strain upon unloading in the polyethylene.

E (MPa)	Poisson's ratio	Yield stress at zero plastic strain-(MPa)	Kinematic hardening parameter C-(MPa)	Gamma
34475.798	0.46	18.8	22359	49.145

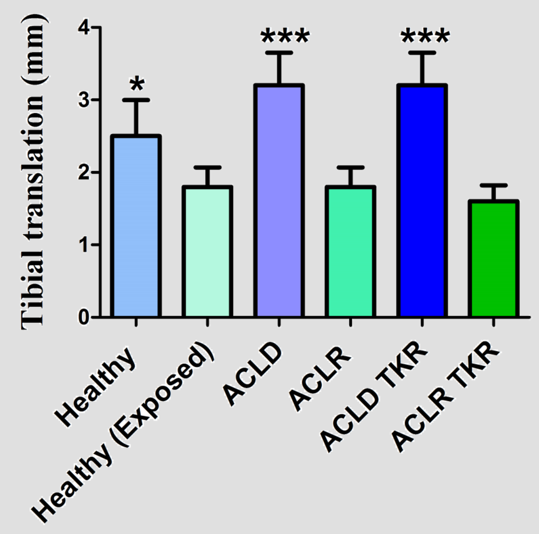
Table 1. Summary of the optimised model parameters for the non-linear kinematic hardening model to represent the material properties of the UHMWPE fibre.

Fig 6. Results of the non-linear isometric kinematic hardening model predicted the cyclic behaviour of the UHMWPE fibre construct



The cadaver trials found no significant difference between the anterior tibial translation of the ACL intact (ACLI) knee after exposure (control group) to the ACLR and ACLR TKR groups.

Fig 7. Anterior tibial translation (laxity) of the ACLI, ACLD, ACLD TKR and ACLR TKR cadaver knees



CONCLUSIONS

- The non-linear force-elongation properties of the native ACL could potentially be reproduced by an artificial ACL reconstruction system in the ACL-deficient knees.
- A non-linear isotropic kinematic hardening model predicted the cyclic behavior of UHMWPE fiber construct to within 24%.

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