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Effect of joint laxity on polyethylene wear in total knee replacement

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ABSTRACT

Experimental simulator studies are frequently performed to evaluate wear behavior in total knee replacement. It is vital that the simulation conditions match the physiological situation as closely as possible. To date, few experimental wear studies have examined the effects of joint laxity on wear and joint kinematics and the absence of the anterior cruciate ligament has not been sufficiently taken into account in simulator wear studies.

The aim of this study was to investigate different ligament and soft tissue models with respect to wear and kinematics.

A virtual soft tissue control system was used to simulate different motion restraints in a force-controlled knee wear simulator.

The application of more realistic and sophisticated ligament models that considered the absence of anterior cruciate ligament lead to a significant increase in polyethylene wear (p=0.02) and joint kinematics ($p<0.01$). We recommend the use of more complex ligament models to appropriately simulate the function of the human knee joint and to evaluate the wear behavior of total knee replacements. A feasible simulation model is presented.

1. Introduction

Wear of ultrahigh molecular weight polyethylene (PE) in total knee replacement (TKR) is a particularly important factor for the longevity of the implant (Argenson et al., 1992; Blunn et al., 1997; Engh et al., 1992). Wear debris has been shown to lead to cellular reactions that result in periprosthetic bone loss and loosening of implants (Amstutz et al., 1992; Revell et al., 1997). Preclinical wear testing of TKR is important for the provision of appropriate wear models and for the investigation of wear behavior. Knee simulators are used for such tests. Several factors that influence wear such as implant design, manufacturing, sterilization method, joint lubrication, patient weight, and activity level have been studied (Schmalzried et al., 1999). Wear is also highly dependent on kinematics; increased AP translation (anterior–posterior translation) and IE rotation (internal–external rotation) have been reported to raise PE wear in TKR (Kawanabe et al., 2001; McEwen et al., 2005). The motion of the natural knee is governed by active forces that originate from the muscles as well as dynamic and gravitational forces (Mikosz et al., 1988; Morrison, 1970). These forces must be restrained by the passive structure of the joint. Due to their passive elastic behavior, the soft tissues, and in particular the ligaments, provide the restraining forces needed to balance the active forces during physiological motion (Ma et al., 2003; Shelburne et al., 2004). Several studies have described the soft tissue reaction in the human knee as a non-linear elastic material, and have highlighted the importance of the cruciate ligaments (Butler et al., 1980; Fukubayashi et al., 1982; Kanamori et al., 2002; Markolf et al., 1984; Shoemaker et al., 1985; Woo et al., 2002); in the absence of the anterior cruciate ligament (ACL) joint laxity is increased. This is of particular importance because the ACL is commonly sacrificed during the implantation of a TKR. Increased laxity will directly affect the joint kinematics (Walker et al., 2003). In wear simulator studies increased AP translations and IE rotations of the TKR have been reported when laxity was raised (Haider et al., 2006; White et al., 2006). However, the effect of increased laxity on implant wear is unknown. Furthermore, most wear studies to date have not sufficiently simulated the ligaments (D'Lima et al., 2001; Laurent et al., 2003; Tsukamoto et al., 2006). At best, mechanical springs were used to replicate the ligaments (Benson et al., 2001; Schwenke et al., 2005; Walker et al., 1997). However, the linear behavior of mechanical springs does not represent the asymmetric non-linear soft tissue motion restraint in vivo. Additionally, motion restrain caused by the springs used in those studies was too high and both physiological and postoperative joint laxity

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were not sufficiently represented (Butler et al., 1980; Fukubayashi et al., 1982; Kanamori et al., 2002; Markolf et al., 1981; Shoemaker et al., 1985; Woo et al., 2002).

This study was designed to demonstrate that applying a realistic asymmetric non-linear soft tissue motion restraint and including the absence of the ACL will (1) increase joint kinematics (AP translation and IE rotation) and thus (2) increase PE wear in simulator studies. To tests these hypotheses, a wear study based on two different soft tissue models was performed using a force-controlled knee simulator.

2. Materials and methods

Two wear tests were performed to investigate the effect of different laxities on PE wear and joint kinematics. For the first test linear motion restraints of 30 N/mm for AP translation and 0.6 Nm/° for IE rotation, according to ISO standard 14243-1:2002(E), were chosen to simulate the intact cruciate ligaments. For the second test, asymmetric non-linear motion restraints were adopted from biomechanical studies that simulated the clinical situation of a sectioned ACL (Fukubayashi et al., 1982; Kanamori et al., 2002). The ligament models are shown in Fig. 1 (AP translation) and Fig. 2 (IE rotation).

Motion restraints for sectioned ACL were implemented according to the following polynomial equations:

For AP motion the restraining force (RF_{AP}) is valid in a specific value range (V_{AP}) and depends on the AP displacement (x_{AP}):

$$RF_{AP} = 5.66 \times 10^{-4}\ \frac{N}{mm^5} \times x_{AP}{}^5 - 2.02 \times 10^{-2}\ \frac{N}{mm^4} \times x_{AP}{}^4 + 0.27\ \frac{N}{mm^3} \times x_{AP}{}^3 - 1.09\ \frac{N}{mm^2} \times x_{AP}{}^2 + 2.60\ \frac{N}{mm} \times x_{AP} + 1.90\ N \quad (1)$$

with

$$V_{AP} = \{x_{AP} \in \mathbb{R} \backslash -10 < x_{AP} < 20\} \quad (2)$$

For IE motion the restraining torque (RT_{IE}) depends on IE rotation (x_{IE}), valid for a specific value range (V_{IE})

$$RT_{IE} = 0.20 \times 10^{-5}\ \frac{Nm}{deg^5} \times x_{IE}{}^5 + 0.25 \times 10^{-4}\ \frac{Nm}{deg^4} \times x_{IE}{}^4 - 4.13 \times 10^{-4}\ \frac{Nm}{deg^3} \times x_{IE}{}^3 - 2.32 \times 10^{-3}\ \frac{Nm}{deg^2} \times x_{IE}{}^2 + 0.31\ \frac{Nm}{deg} \times x_{IE} - 1.68\ Nm \quad (3)$$

with

$$V_{IE} = \{x_{IE} \in \mathbb{R} \backslash -20 < x_{IE} < 20\} \quad (4)$$

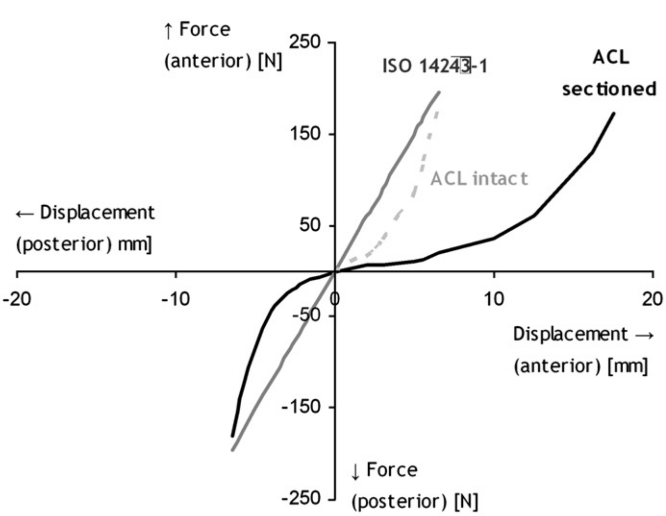

Fig. 1. Motion restraint for AP translation according to the 14243-1:2002(E) is based on a linear approximation of the tibial anterior–posterior displacement when the ACL is intact. A sectioned ACL increases tibial anterior–posterior displacement. In the neutral zone (displacement close to zero) the slope of the curve according to the 14243-1:2002(E) standard is much higher compared to the asymmetric and non-linear curves given by Fukubayashi et al. (1982) even for an intact ACL.

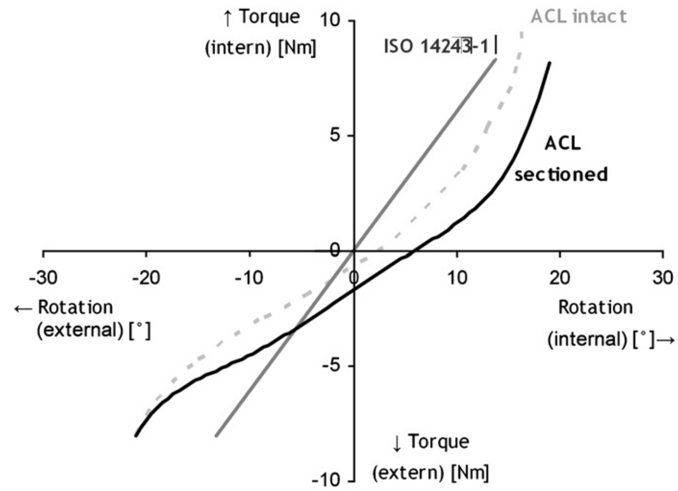

Fig. 2. Motion restraint for the IE rotation according to the 14243-1:2002(E) is based on a linear approximation of the tibial IE rotation. Close to the neutral zone the motions restraint for an intact or sectioned ACL is almost linear. Nevertheless, the slope of the curve according to the 14243-1:2002(E) standard is much higher compared to the curves of an intact or sectioned ACL as given by Kanamori et al. (2002).

Fig. 3. The ultracongruent fixed bearing TKR implant used in the study (mounted in a wear station of the simulator).

The only parameter to be altered in both tests was the motion restraint. This allowed different motion restraints to be investigated separately.

For each wear test, three wear specimens and one soak control specimen were used. An ultracongruent fixed bearing design (Columbus® UC, Aesculap AG, Tuttlingen, Germany) was evaluated in this study (Fig. 3). The medium-sized components were manufactured in a similar manner: the femoral components and