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Quadriceps force during knee extension in different replacement scenarios with a modular partial prosthesis

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ABSTRACT

Background: Previous biomechanical studies have shown that bi-cruciate retaining knee replacement does not significantly alter normal knee kinematics, however, there are no data on the influence of a combined medial and patellofemoral bi-compartimental arthroplasty. The purpose of this in vitro study was to evaluate the effect of different replacement scenarios with a modular partial knee replacement system on the amount of quadriceps force required to extend the knee during an isokinetic extension cycle.

Methods: Ten human knee specimens were tested in a kinematic knee simulator under (1) physiologic condition and after subsequent implantation of (2) a medial unicondylar and (3) a trochlear replacement. An isokinetic extension cycle of the knee with a constant extension moment of 31 Nm was simulated. The resulting quadriceps extension force was measured from 120° to full knee extension.

Findings: The quadriceps force curve described a typically sinusoidal characteristic before and after each replacement scenario. The isolated medial replacement resulted in a slightly, but significantly higher maximum quadriceps force (1510 N vs. 1585 N, $P = 0.006$) as well as the subsequent trochlear replacement showed an additional increase (1801 N, $P = 0.008$). However, for both replacements no significant difference to the untreated condition could be detected in mid-flexion (10–50°).

Interpretation: When considering a bi-compartimental replacement an increase of required maximum quadriceps force needed to extend the knee has to keep in mind. However, the close to physiological movement in mid-flexion suggests that patients with a bi-crutiate retaining arthroplasty might have an advantage in knee stability compared to total knee arthroplasty.

1. Introduction

When considering knee replacement surgery, orthopaedic surgeons have the option to undertake a total knee arthroplasty (TKA) or a partial knee replacement. As reported earlier, even patients with excellent results after TKA have an altered walking pattern with less flexion, a shorter swing phase, and weaker extension strength in the operated knee (Andriacchi, 1993; Li et al., 2013).

Besides the prosthetic design, especially the loss of proprioreception and alternations in lever arms and extension moments are responsible for said abnormal muscle function after TKA (Li et al., 2013; Ostermeier and Stukenborg-Colsman, 2011). In this context the anterior cruciate ligament (ACL) is of special interest. When the ACL is sacrificed, the lever arm of the extensor mechanism is reduced due to a paradoxical anterior movement of the femur relative to the tibia during flexion, which results in higher quadriceps muscle forces required to extend the knee (Dennis et al., 1998; Heyse et al., 2010a, 2010b; Lewandowski et al., 1997; Ostermeier and Stukenborg-Colsman, 2011; Ostermeier et al., 2004).

After a period of diminishing popularity, the interest in bi-cruciate retaining partial knee replacement has increased in recent years (Zanasi, 2011). In certain patients, the medial and patellofemoral (PF) compartments are affected by osteoarthritis, but the ACL and lateral compartment remain healthy. These patients are candidates for a medial plus PF bi-compartmental knee replacement to prevent or postpone the TKA and to preserve the normal ligament structures and proprioception of the knee (Heyse et al., 2010a, 2010b; Rolston et al., 2007). The clinical experiences with new knee designs indicate a high level of function and knee kinematics in patients retaining essential features of the normal knee motion (Leffler et al., 2012; Thienpont and Price 2013).

Previous biomechanical studies have shown that bi-cruciate retaining unicondylar knee replacement does not alter normal knee kinematics during simulated stair climbing in a cadaver model (Patil et al., 2005). No significant differences in tibial axial rotation, femoral rollback or quadriceps tension were noted between the physiological and unicompartmental conditions.

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However there are no biomechanical data on the influence of a combined medial and PF bi-compartimental arthroplasty and its effect on the required quadriceps extension force.

Thus, the purpose of this in vitro study was to evaluate the effect of the different components in a modular partial knee replacement system on the amount of quadriceps force required to extend the knee during an isokinetic extension cycle.

2. Methods

The experimental set-up and test cycle was used in this study were the same as previously reported by Ostermeier et al. It is described to simulate an isokinetic extension cycle of the knee, which allows an approximation of loadings close to the magnitude of the physiological forces and moments about the knee. In this study, ten fresh frozen adult knee specimens of nearly the same size (mean age = 75 (64–85) years, 5 male and 5 female) fulfilling the criteria of an intact periarticular musculature and an intact capsule and ligament apparatus were used. Furthermore, no significant osteoarthritis was present. The specimens were prepared according to standard protocols with transection of the femur and tibia 25 cm proximally and distally to the knee joint line. The skin and subcutaneous tissue were removed preserving the muscles, articular capsule, ligaments and tendons. The specimens were mounted into our in-vitro knee simulator in which the said isokinetic flexion–extension movements were simulated (Fig. 1). The specimens were positioned with the femur fixed horizontally and the patella facing downwards. The femoral and tibial bone stumps were fixed with bone cement in metal sleeves to reproduce the same positioning on every test cycle. The tibia was attached to the simulator at mid-length by means of a linear rotational bearing. This allowed axial sliding and turning as well as rotation transverse to the axis of the tibia. The bearing itself was attached to a swing arm that allowed motion in the varus/valgus plane. The characteristics of this arrangement were described to give complete freedom of motion of the joint, with the exception of flexion–extension, which is determined by the position of the swing-arm. The swing arm was equipped with a strain-gauge-based load-measuring device that allowed continuous monitoring of a torsional moment applied to the tibia. Tibial movement was provoked by the coordinated activation of 3 hydraulic cylinders, which were attached to the specimens' tendons by special clamps. By this, quadriceps muscle force and a co-contraction of the hamstring muscles were simulated as well as an external flexion moment was applied. One complete test cycle simulated an isokinetic extension cycle from 120° knee flexion to full extension. The quadriceps cylinder thereby applied sufficient force to the quadriceps tendon in a closed-loop control cycle to generate a constant knee extension moment of 31 Nm. The hamstring cylinder simulated co-contraction of the hamstring muscles with a constant co-contractive flexion force of 100 N. Initially, the swing arm was activated to bring the specimen into a position of 120° of flexion. In our standard protocol, the quadriceps cylinder was then activated in feedback control to provide a constant net joint extension moment by applying the constant extension moment at the swing arm. The joint moment was measured by the load cell in the swing arm, allowing continuous control of quadriceps force throughout the complete motion to maintain the nominal extension moment of 31 Nm, as reported earlier. This constant extension moment was resisted by a constant swing arm flexion moment, which was generated by a third hydraulic cylinder, creating an isokinetic extension movement. Measurement of the resulting quadriceps was performed using a load cell (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany, accuracy 0.1 N) attached between the tendon clamp and the quadriceps cylinder. The data was collected at a frequency of 10 Hz. The degree of knee flexion was recorded using a custom-made voltage goniometer attached to the tibial swing arm at a frequency of 10 Hz and with an accuracy of 0.05°. All test cycles were run at room temperature.

The quadriceps forces of all specimens were at first measured in the native physiological joint. Subsequently, a medial unicompartmental knee replacement (Sigma® PFC High Performance Partial Knee; DePuy Orthopaedics, Kirkel, Germany) was implanted by the same surgical team without bone cement according to the manufacturer's guidelines. The prosthesis system offers a fixed polyethylene inlay. The tibia base-plate was implanted according to the anatomical joint line and posterior tibial slope. The femoral component position was adjusted to the tibial component in flexion and extension. The knee capsule and soft tissues were readapted and the specimen was remounted in the simulator. The test cycle was repeated as for the physiological knee.

That followed an additional implantation of the trochlear component (Sigma® PFC High Performance Partial Knee Trochlear Component; DePuy Orthopaedics, Kirkel, Germany) in every specimen. This again was performed by the same surgical team according to the manufactures' protocol without bone cement and without an additional patella resurfacing. The patella was freed from osteophytes and readjusted carefully to the trochlear groove. After implantation and closure of the capsule, the specimen was remounted in the simulator and the test cycles were repeated identically. The mean quadriceps forces of all test cycles were calculated.

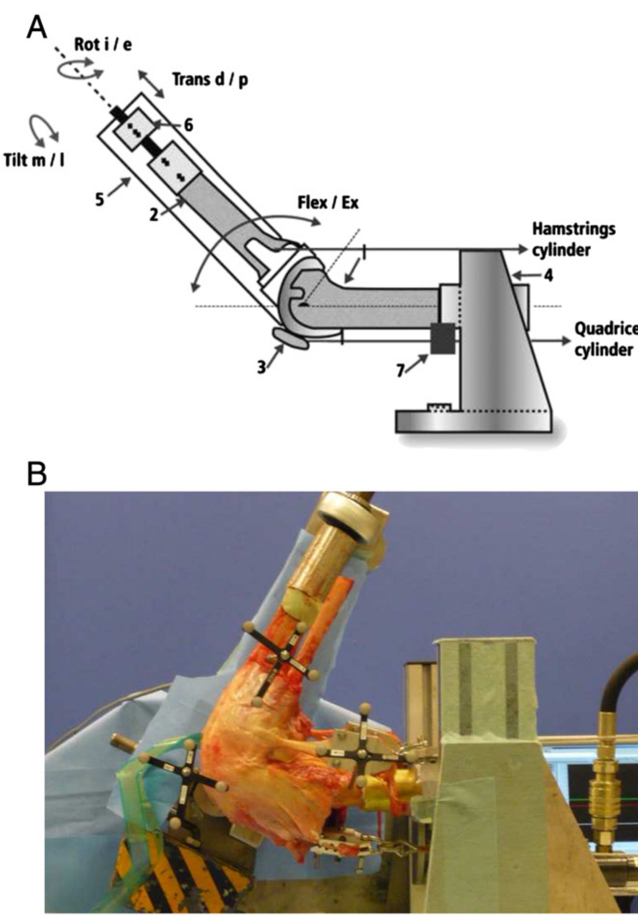

Fig. 1. A. Schematic side view of the experimental set-up; and B. Photograph of a specimen mounted in the in-vitro knee simulator. The specimen is brought from a position of 120° of flexion to full extension by applying force on the quadriceps cylinder, providing a constant joint extension moment (31 Nm) resisted by the swing arm. An additional flexion force is applied by the hamstrings cylinder. 1) femur, 2) tibia, 3) patella, 4) femur frame 5) swing arm, 6) strain gauge, and 7) load cell.