In vitro investigation of knee joint kinematics following cruciate retaining versus cruciate sacrificing total knee arthroplasty

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The aim of this biomechanical study was to investigate knee joint kinematics following total knee arthroplasty.

We compared eight congruent posterior cruciate ligament retaining and four ultracongruent cruciate sacrificing Natural Knee prostheses to the untreated human cadaveric knee joint. A six-degree-of-freedom testing device was used to evaluate knee joint kinematics with a load of 300 Newton and without load application (0 Newton). Statistical analysis was performed using the Wilcoxon rank sum test.

A significant increase in antero-posterior translation and tibial rotation was seen in both types of total knee arthroplasty. Implantation of the ultracongruent prosthesis was followed by distinctly more kinematic changes in comparison to the congruent prosthesis. Load application of 300 Newton leads to an anterior dislocation of the femoral component of the ultracongruent prosthesis at 60° of flexion *in vitro*, indicating an increased demand of compensatory muscular activity *in vivo*.

INTRODUCTION

Total knee arthroplasty [TKA] has become a standard procedure in the surgical treatment of osteoarthritis and rheumatoid arthritis of the knee joint. Better knowledge of biomechanics and better design have improved clinical outcome [13].

The issue of retaining or sacrificing the posterior cruciate ligament [PCL] remains controversial [13]. The important point about the PCL following cruciate retaining TKA is not its physical presence, but its functional role [19]. Some evidence seems to prove that it is generally impossibe to restore a normal strain pattern following cruciate ligament retaining TKA [10, 17]. It is however generally accepted that both cruciate ligaments balance the opposing needs for stability and mobility in the complex kinematic system of the knee joint [12]. They are the main stabilizers limiting anterior-posterior translation [7]. Furthermore they control rollback [16] and tibial rotation [1]. In addition, both cruciate ligaments also have proprioceptive functions [4].

The degree of congruency of an ideal prosthesis design for knee replacement also remains controversial, as well as the interaction with the PCL. Lack of congruency might lead to increased penetration wear [20]. A high level of congruency as in PCL-retaining designs might result in an increased posterior polyethylene wear [6] or rupture of the PCL [13] due to an imbalanced interaction with its function. An ultra-congruent implant certainly eliminates rollback and hence limits range of motion [2, 18].

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The aim of this biomechanical *in vitro* study was to compare the kinematics of two different types of the Natural Knee [NK] TKA system (PCL retaining with a congruent inlay, versus PCL sacrificing with an ultracongruent inlay) to the native knee joint and to evaluate the influence of resection of the anterior cruciate ligament [ACL] or of both cruciate ligaments, on the passive knee joint kinematics after TKA.

MATERIAL AND METHODS

The investigation was performed in the facilities of the Department of Traumatology and the Department of Forensic Medicine of the Semmelweis University Budapest (Budapest, Hungary).

The NK congruent and ultracongruent total condylar prostheses (Intermedics Orthopedics, Austin, TX, USA) were studied. They are designed as modular, non-constrained TKA systems with a fixed tibial plateau. The tibial polyethylene insert of the NK ultracongruent prosthesis is markedly dished and supplied with an additional anterior build-up, creating a higher level of congruency as compared to the NK congruent prosthesis [9]. In both cases the ACL needs to be resected. The NK ultra-congruent prosthesis furthermore is designed for the sacrifice of the PCL.

Twelve fresh human cadaveric knee joints with intact soft tissue covering were replaced with an NK knee : 8 congruent and 4 ultra-congruent knees were implanted. All knee joints were free of arthritic changes, ligamentous instability and deformity and were used within the first 24 hours after death. In all cases a medial parapatellar approach, a standard insertion technique and standard bone cementing (PMMA) technique were used.

The choice of implant size followed the guidelines of the manufacturer. Only nine to eleven millimeter [mm] polyethylene inserts were used, and correct restoration of the joint line level was obtained in all cases. The individual preoperative tibial slope and the position of the joint line were checked by intra-operative biplanar radiography and restored as accurately as possible. Tibial slope was controlled on lateral radiographs, and joint line position on antero-posterior radiographs, the tip of the fibula serving as a reference point. Restoration of both joint line and tibial slope was considered necessary, in order to avoid the adverse effects of an overly tight or lax PCL [6, 17].

Stability of the PCL and the collateral ligaments of the cadaveric knees following TKA was achieved by
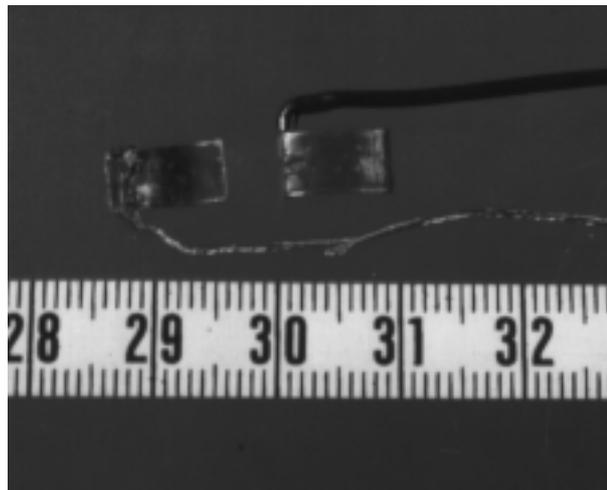

Fig. 1. — Implantable force transducer (IFT)

tensioning the remaining soft tissues, and by management of the flexion/extension gaps at the time of surgery. Since all knees were inherently stable and deformity was absent, no supplementary soft tissue balancing was needed. The femoral component was placed at approximately 3° of external rotation with respect to the posterior condylar line, but this was not specifically analysed.

Pre- and postoperative strain patterns of the PCL were evaluated using implantable force transducers (IFT) to confirm the correctness of the surgical soft tissue balancing (fig 1) [8]. The IFT's were placed via defined approaches in a standardised manner in the postero-medial bundle of the PCL and were kept in place during TKA. Calibration of the IFT's was done before TKA was performed. In none of the cases was a supplementary PCL release performed, resulting in a maximal increase of 14% in the PCL strain at 80° of flexion following TKA using the NK congruent prosthesis. Nevertheless, this PCL strain alteration was found to be non-significant, suggesting that TKA using the NK congruent prosthesis allowed PCL strain to be close to normal as the knee flexed. Furthermore, according to clinical criteria (manual palpation of the ligament and visualisation of the flexion/extension gaps) none of the knees revealed clinical signs of ligamentous mismatch.

Kinematics of the knee were evaluated using a six-degree-of-freedom manipulator (fig 2), which was designed in collaboration with the Fraunhofer Institute for Biomedical Research (St. Ingbert, Germany). This testing device enables the measurement of knee kinematics (extension/flexion, anterior/posterior (a/p) translation, femoral and tibial rotation, varus/valgus rotation

Fig. 2. — Six-degree-of-freedom testing device

and medial/lateral translation) at several degrees of flexion in 10° intervals from full extension to 120° of flexion. Furthermore, the device allows the investigation of knee kinematics after axial load application of 300 Newton (N) to the femur to simulate weight-bearing *in vivo* conditions.

Knee joint kinematics were assessed before and after TKA with 300 N and without load application (0 N) three times at each 10° interval. We calculated the average translation and rotation movements at all 10° intervals starting from full extension to 90° of flexion.

The test series allowed investigations of the passive knee joint kinematics with and without load application before and after TKA. Proprioception circuits and consecutive active muscle stabilisation mechanisms did not interfere with the kinematic measurements. Systematic technical errors were reduced by a standardised implantation technique and by standardised assessment (all

TKA's were done by the same orthopaedic surgeon, measurement cycles were done either automatically or by the same group of investigators).

Statistical analysis was performed with the Wilcoxon rank sum test using SAS software programs (SAS Institute, Cary, NC, USA). A value of $p < 0.05$ was considered significant.

RESULTS

We compared the results of the knee joint kinematics before and after TKA specially under loading conditions (300 N). Concerning the restoration of the joint line and the tibial slope, all twelve TKAs were positioned correctly according to clinical and radiographic criteria (see above).
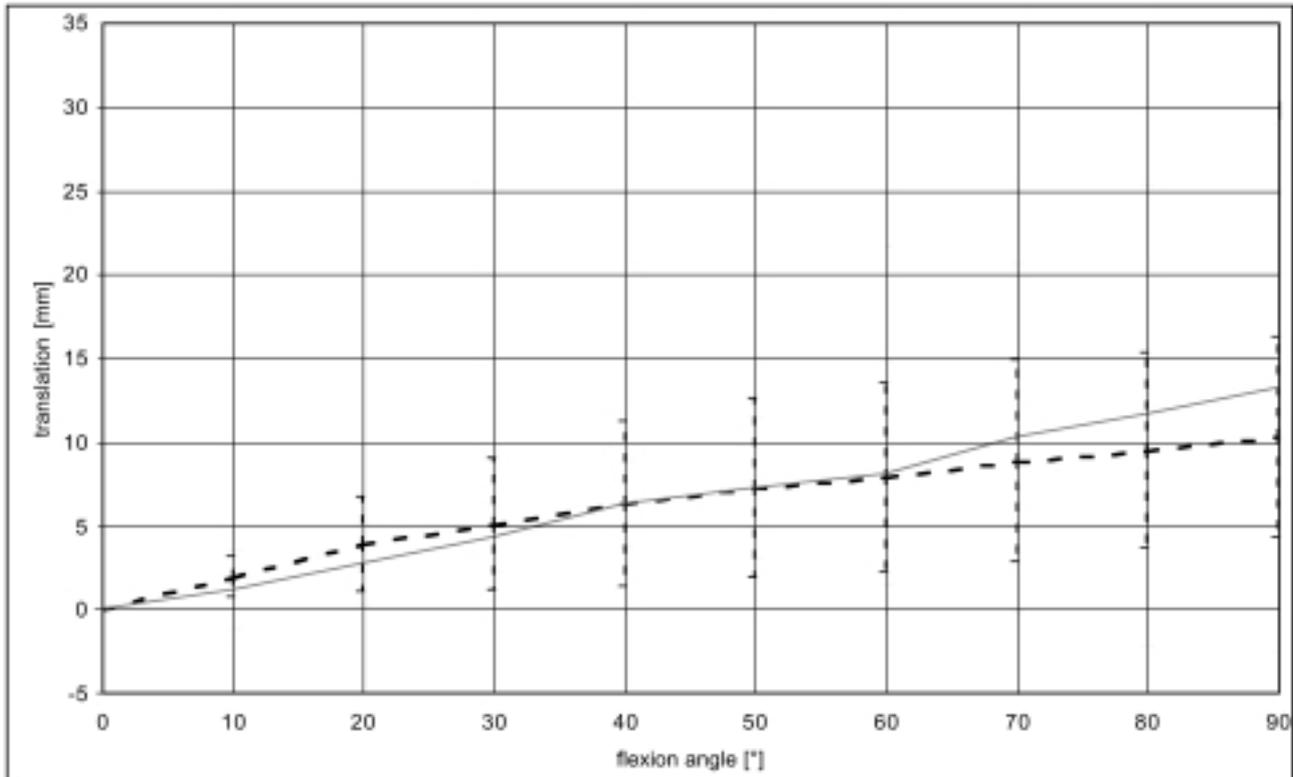
The implantation of the IFT and the capsulotomy did not result in any significant changes in knee joint kinematics ($p > 0.05$).

Femoral rotation, varus/valgus mobility and mediolateral translation did not significant vary in both NK types compared to the native knee ($p > 0.05$). Nevertheless, the sacrifice of both cruciate ligaments (NK ultracongruent prosthesis) influenced rotational and translational mobility more than the sacrifice of the ACL alone (NK congruent prosthesis).

In comparison to the human untreated cadaveric knee joint, the anterior translation of the femur following TKA with the NK congruent prosthesis increased maximally in 90° of flexion to 13.2 mm (standard deviation [sd] : 15.7) under load ($p < 0.05$) and to 10.3 mm (sd : 6.0) without load application ($p < 0.05$) (table I). The maximal increase (compared to the native knee joint) of external rotation of the tibia in 90° of flexion under load application was 14.6° (sd : 11.0) ($p < 0.05$) against 5.1° (sd : 3.0°) increase of internal rotation in full extension without load application ($p > 0.05$) (table II).

Compared to the untreated cadaveric knee joint, the anterior translation of the femur after TKA with the NK ultracongruent prosthesis (ACL and PCL sacrificed) increased to 32.7 mm (sd : 17.4) under load ($p < 0.05$) and up to 23.1 mm (sd : 4.4) without load ($p < 0.05$). Again the maximal difference was reached at 90° of flexion. Beyond 60° of flexion the prosthesis dislocated anteriorly under

Table I. — NK congruent – kinematic change in a/p translation with 300 N [——] and without (0 N) [- - - - -]
load application before and after TKA

load application (table III) and further measurements were considered unreliable. Tibial external rotation was increased to a maximum of 10.2° (sd : 14.8) under load (p > 0.05) and 12° (sd : 5.3) without load application (p < 0.05), both maximal difference values in 90° of flexion (table IV).

DISCUSSION

Several clinical studies have shown similar functional results with PCL retaining and PCL sacrificing TKA (3, 9) and the superiority of either of these designs is not proven. Numerous other clinical and biomechanical studies have postulated such superiority.

Supporters of PCL-retaining TKA systems argue with the persistance of a physiological roll-back mechanism, regular knee joint kinematics (2, 18), and a superior proprioception postoperatively (4). Furthermore, preserving the PCL may support the function of the quadriceps muscle, reduce muscle
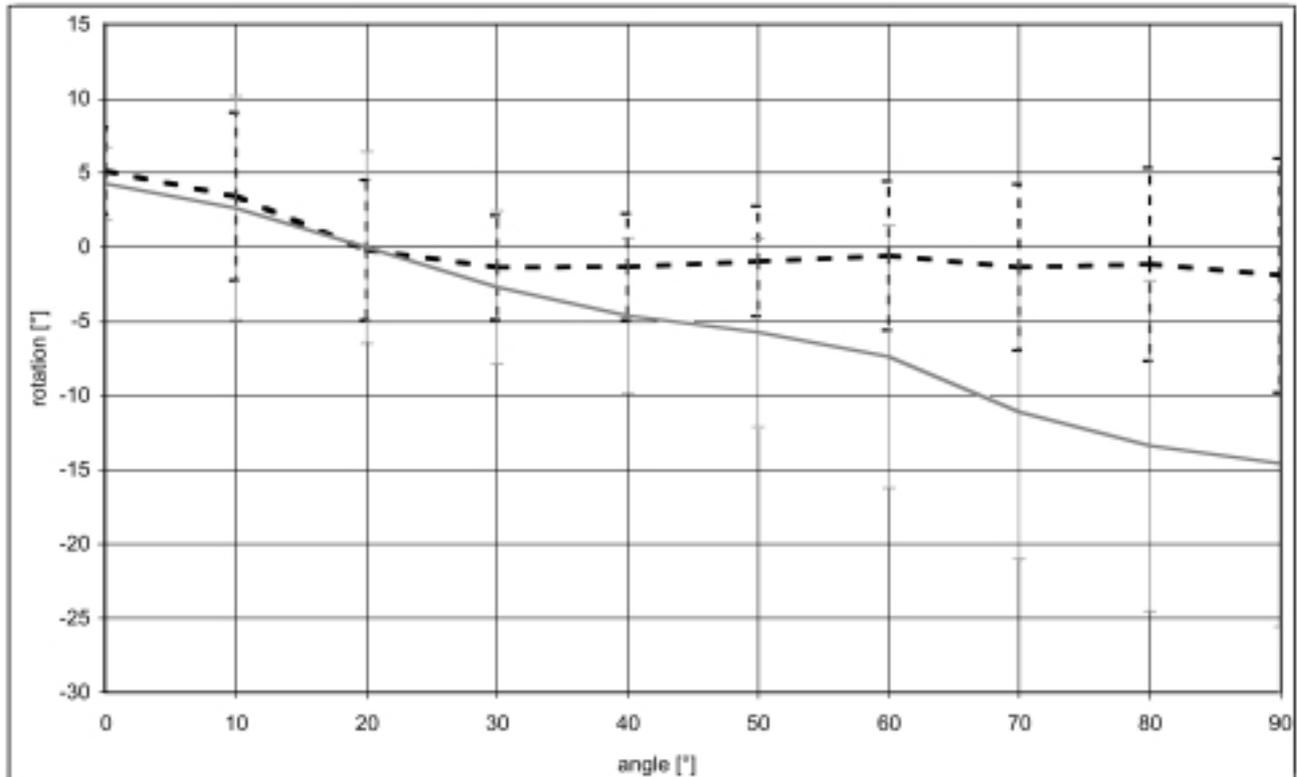
activity and hence lessen shear and tilting forces at the implant-bone interface (5).

The opponents to PCL-retaining TKA systems postulate that it is impossibe to restore the preoperative, normal PCL strain pattern with a TKA prosthesis (10, 17). Decreased tension might compromise function, whereas increased tension might limit rollback (19) and range of motion (6). This is believed to negatively influence the localisation and the amount of shear and compression forces, leading to increased posterior polyethylene wear (6). In addition to this, an improved proprioception following TKA with retained PCL is doubted (14).

Our *in vitro* study using a multidirectional testing device was designed to objectively evaluate the functional role of the PCL in knee kinematics following PCL retaining versus sacrificing TKA.

Our results are valid only as a static *in vitro* study. Due to the specificities of our study setting, fundamental alterations of the results caused by the presence of degenerative joint disease and the

Table II. — NK congruent – kinematic change in tibial rotation with 300 N [———] and without (0 N) [- - - - -]
load application before and after TKA

dynamic influence of the hamstrings and the quadriceps were not taken into account.
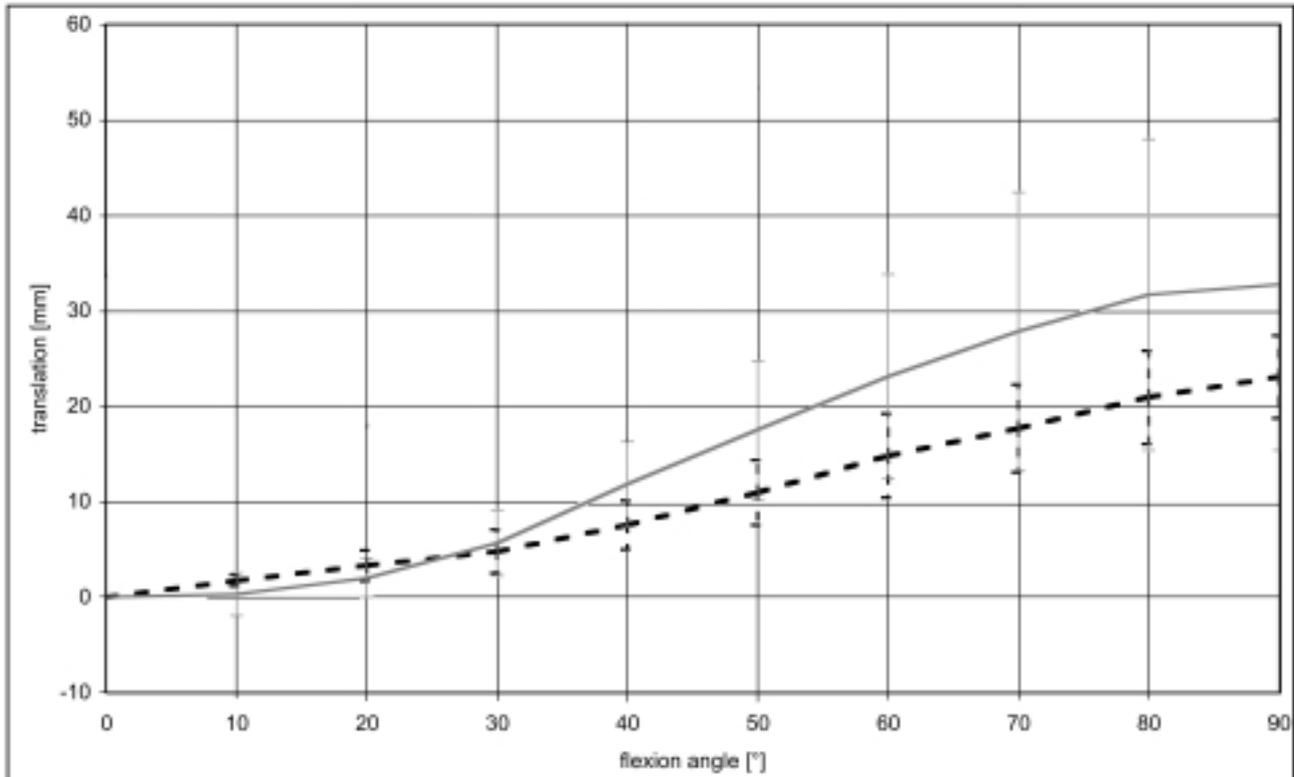
Concerning femoral rotation, varus/valgus mobility and mediolateral translation, there were no significant differences between the two versions of the NK TKA system and the native knee joint. Although we did not find any significant differences, an NK ultracongruent prosthesis with sacrifice of both cruciate ligaments more distinctly influenced rotational and translational movements than a NK congruent prosthesis sacrificing the ACL only. A similar observation was made in an *in vivo* study, showing greater mediolateral and proximal/distal translation after TKA with sacrifice of both cruciate ligaments compared to TKA with retention of the PCL (11). These findings might be explained by the stabilising function of the retained PCL.

Both TKA versions showed a significantly greater anterior translation (with and without load application) than the native knee joint. The NK ultracongruent prosthesis anteriorly dislocated bey-

ond 60° of flexion under axial load of 300 N. This increase in a/p translation *in vitro* might be due to the loss of mechanical stability otherwise provided by the PCL. Similar results were observed in a cadaveric study, also displaying significantly irregular knee joint kinematics after TKA with sacrifice of both cruciate ligaments compared to TKA with retained PCL (18). As a consequence of this increased a/p translation, increased shear, compression and tilting forces might result. Nevertheless the static knee model of this study design does not take into account the dynamic influence of the agonists of both cruciate ligaments, which *in vivo* might limit the amount of a/p translation and its adverse effects.

Concerning tibial rotation after TKA with PCL retention (NK congruent prosthesis), there were only small differences without load application in comparison to the native knee joint. Under load we found a significantly altered external rotation. The NK ultracongruent prosthesis showed with and

Table III. — NK ultracongruent — kinematic change in a/p translation with 300 N [——] and without (0 N) [- - - - -] `
load application before and after TKA

without load application a tibial malrotation comparable to the findings with the PCL-retaining TKA with load application. It displayed a tibial rotation which started in full extension with an altered internal rotation and finished at 90° of flexion with a significantly increased external rotation. These results indicate that both cruciate ligaments do play a major role in conducting tibial rotation. Our findings are partially comparable to those of a biomechanical *in vitro* study, reflecting the importance of the ACL for the resulting knee motion (1).

As shown by the NK ultracongruent prosthesis, TKA systems with fixed bearing and sacrifice of the PCL require a greater amount of intrinsic mechanical stability as compared to PCL retaining TKA designs. Anterior build-up systems (like the NK ultracongruent prosthesis) as well as cam-post systems theoretically can provide such a mechanical stability *in vivo* as they were both shown to perform equally well compared with PCL-retaining TKA designs (3, 9). Nevertheless, the anterior build-

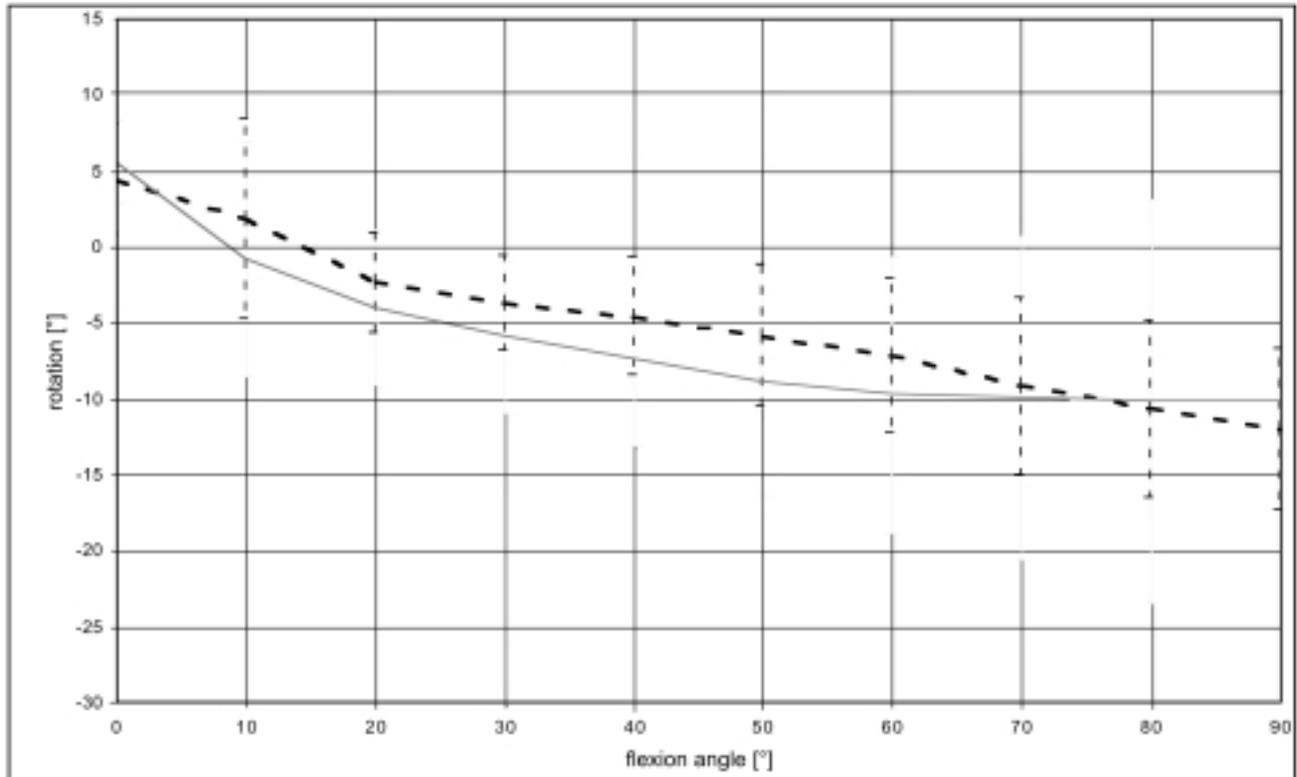up system used in this study failed *in vitro* to provide the required stability.

In summary, a major increase of a/p translation could be observed after TKA with PCL sacrificing. Axial load application of 300 N to the femur resulted in prosthesis failure due to anterior dislocation. In contrast to this, PCL preservation in case of NK congruent TKA was followed by kinematic changes to a lesser degree.

These findings and their implications concerning the generated differences in the resulting muscle forces after cruciate-retaining versus cruciate-sacrificing TKA are supported by clinical (5) and *in vitro* (15) investigations which also showed reduced muscle activity following TKA with PCL preservation compared to its sacrifice.

CONCLUSION

The implantation of a TKA system requiring sacrifice of the PCL (NK ultracongruent prosthesis

Table IV. — NK ultracongruent — kinematic change in tibial rotation with 300 N [———] and without (0 N) [- - - - -] load application before and after TKA

with a highly congruent design) creates distinctly irregular knee joint kinematics. Implantation of a less congruent design with preservation of the PCL (NK congruent prosthesis) shows *in vitro* less alteration of the passive knee joint kinematics, thus eventually demanding a lowered active muscular compensation mechanism *in vivo*.

As a major limitation of the study design, the possibility of fundamental alterations of the results caused both by dynamic influences and by the presence of degenerative joint diseases was not taken into account. Consequently, the findings of this study need to be seen in the context of a cadaveric, static study design.

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