The influence of turning

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Knee rotation during a weightbearing activity: Influence of turning.
Gait Posture 2008; 28: 472-7
ABSTRACT

Background: Kinematic studies, in which mobile- and fixed-bearing total knee arthroplasty (TKA) were compared, showed controversial results with respect to axial femorotibial rotation. However, all studies focused only on straight ahead tasks, which may underestimate possible differences in freedom of rotation. The purpose of this study was to investigate the influence of turning on normal axial knee rotation. If large differences across tasks were to be found, this would support the use of this task in the evaluation of in-vivo TKA kinematics.

Methods: In 15 healthy persons, crossover and sidestep turns were added to a standardized chair rise. Three dimensional knee angles were recorded using an optoelectronic motion analysis system, and a noninvasive epicondylar frame was developed to track the femur.

Results: Compared to knee rotation during the straight ahead task, average peak tibial internal rotation increased during a crossover turn ($p<0.001$), as did peak external tibia rotation during a sidestep turn ($p<0.001$). The combined range of axial rotation for both turning tasks together was 20.9 degrees, versus 13.5 degrees for the straight ahead task ($p<0.001$).

Conclusions: The turning maneuvers in this study induced a large range of axial knee rotation, so they could be important in studies comparing freedom of rotation in mobile- and fixed-bearing TKA.
INTRODUCTION

Total knee arthroplasty (TKA) is frequently applied to patients with end-stage arthritic disorders of the knee, and is considered to be a successful operation.\(^1\) Nevertheless revision surgery is necessary in 8 percent of cases after 10 years, with aseptic loosening being the major complication after TKA, causing 44 percent of knee revisions.\(^2\) As the limits of current fixed-bearing prostheses are defined, interest in mobile-bearing has been regained.\(^3\) In contrast to fixed polyethylene bearings, a mobile insert is able to axially rotate (tibial internal/external rotation) on the metal tibial component of the prosthesis. This mobility allows torque stresses to be transferred to the soft tissues, which is hypothesized to reduce loosening stresses at the bone-implant surface.\(^4-5\) Since no long-term controlled clinical trials have yet demonstrated the superiority of the design, mobile-bearing TKA remains a subject of debate.

The reports from in-vivo kinematic studies, in which mobile- and fixed-bearing prostheses were compared, are contradictory. Some reported significant more axial rotation in the mobile-bearing design.\(^6-7\) Ranawat et al. found a mean tibial internal rotation of 4.1 degrees for a fixed-bearing TKA, and 7.3 degrees for a mobile-bearing TKA during a deep knee bend. Others did not show differences in rotational mobility between mobile- and fixed-bearing designs.\(^8-9\) Dennis et al. found, that maximum rotation angles in 76 posterior-cruciate sacrificed mobile-bearing TKA’s and 212 posterior-stabilized fixed-bearing TKA’s were exactly the same (5.5 degrees of internal rotation and 2.1 degrees of external rotation, during a
deep knee bend). However, all above-mentioned studies focused only on straight ahead tasks, and may therefore underestimate possible differences in freedom of axial rotation. In the kinematic evaluation of TKA, especially when axial rotation is investigated, it may be necessary to specifically study turning tasks.

The importance of turning steps during activities of daily living was emphasized in a video analysis by Glaister et al.\textsuperscript{10} For instance, during walking through a cafeteria, up to 50 percent of steps taken were turning steps. Only a few studies have been focused on the physiological knee mechanics that are associated with turning. Orendurff et al.\textsuperscript{11} studied the joint mechanics of walking a circular 1-metre radius path, but data on axial knee rotation were lacking. Houck et al.\textsuperscript{12} studied knee angles and moments during 45-degree sidestep and crossover cuts, while stepping down, and found no differences in axial rotation. Late stance was not evaluated, although in an earlier study the same authors reported more tibial internal rotation at 70 percent of stance during crossover cutting compared to walking.\textsuperscript{13} So, current literature does not support the use of turning tasks in the kinematic evaluation of TKA designs to find possible differences between designs with respect to axial rotation. However, no study utilized full turning tasks and data on physiologic axial knee rotation associated with partial turning were incomplete.

One reason why turning tasks may be studied less is that measuring axial knee rotation in-vivo is challenging. Sophisticated techniques, using natural ‘internal’ markers,
have provided accurate information on patterns of normal knee movement.\textsuperscript{18-21} However, with respect to movements related to daily living, fluoroscopy and MRI have distinct disadvantages. A major problem using optoelectronic recordings is the existence of a soft tissue artifact by surface markers,\textsuperscript{14} which is even more of a problem when studying cutting motions.\textsuperscript{15} Marker attachment on cortical bone pins may be the ideal solution,\textsuperscript{16} but has obvious ethical and practical disadvantages. Houck et al.\textsuperscript{17} developed the Femoral Tracking Device (FTD) with a rotational accuracy of less than 3 degrees in the first 85 percent of stance during walking. Therefore, the FTD-method serves as a practical alternative to studying tasks with sufficient amounts of axial knee rotational.

The purpose of this study was to compare axial knee rotation during a crossover turning and sidestep turning task with the same task performed straight ahead. Healthy volunteers added standardized turns to the performance of a chair rise. Among common activities of daily living, chair rising covers a unique combination of moments and joint angles.\textsuperscript{22} Our hypothesis was, that turning tasks would result in different peak rotation angles. More specifically, we expected tibial internal rotation to increase during a crossover turn, and tibial external rotation to increase during a sidestep turn. If large differences across tasks were to be found, this would support the use of such specific tasks in the evaluation of \textit{in vivo} kinematics of fixed- and mobile-bearing knee prostheses.
MATERIAL AND METHODS

Subjects
Fifteen healthy volunteers (six females, nine males), who had no history of knee complaints, participated in the study. Their average age was 33.4 years (range 24-63) and their average body mass index was 23.3 (range 18-25). All subjects gave informed consent and the local medical ethical board approved the study protocol.

Optoelectronic and force plate recordings
An OptoTrak motion analysis system (model 3020, Northern Digital Inc., Waterloo, Ontario, Canada) recorded the three-dimensional position of light-emitting diode markers. A sampling rate of 50 Hz was used. A 51 x 46.5 cm force plate (AMTI, Watertown, Massachusetts, USA) recorded three-dimensional ground reaction forces, sampled at 1000 Hz. One millisecond synchronization was ensured, while simultaneous video recordings for monitoring were synchronized at 10 milliseconds. Offline all data were low pass filtered at 10 Hz.

Kinematic modeling
We used a noninvasive stiff lightweight epicondylar frame of aluminum and Delrin (Fig. 2.1), which we developed as a modification of the Femoral Tracking Device validated by Houck et al. One modification in this Femoral Epicondylar Frame includes its attachment on individually molded thermoplastic shells around the femoral epicondyles. A mechanism similar to a cramp, which is tightened using a torque wrench to monitor the applied torque (10-15 cNm), forms another modification.
A cluster of three markers was rigidly attached to the frame. A fourth marker was attached to the skin over the greater trochanter. Another cluster of three markers was positioned over the middle lateral shank, fixated to the body by an elasticized band strapped around the shank.23

An open source Matlab software program, BodyMech (www.bodymech.nl), was used to calculate three-dimensional knee kinematics.24 Tibia and femur were considered to be rigid bodies with a local coordinate system, defined by anatomical points.25 Coordinates of the two points, where the virtual axis of the device entered the femoral epicondyles, were calculated from the frame markers. The greater trochanter instead of femoral head was used for the femoral longitudinal axis definition. The shank markers were anatomically calibrated using the tibial tuberosity and medial and lateral malleoli. Knee kinematics followed from the relative orientation of the tibia with respect to the femur, while decomposition into Euler angles (flexion-extension, abduction-adduction, internal-external rotation) was applied following the Grood and Suntay convention.26

Procedures
The subjects were asked to perform three tasks, all-starting with rising from a chair. Chair height was adjusted to 90 percent of the lower leg length. Only the right knee of all subjects was measured. Both feet, which were aligned with the line of progression, became weightbearing at the same time, the right foot being on the force plate. In the first task, straight ahead (SA), rising from a chair was followed by stepping forward. In the second task, a crossover turn (CT), the first step was with
the left foot to the right side. For the third task, a sidestep turn (ST), the first step was with the left foot to the left side. In both turning tasks, the left foot landed at 60 degrees with the line of progression, indicated by lines on the floor (Fig. 3.1). Each turn was completed to 90 degrees by a step with the right foot. The tasks were performed at a self-selected speed and consisted of three trials, preceded by practice trials. Within-test reliability for the range of axial knee rotation, by means of intraclass correlation coefficients (95 percent confidence interval), revealed good results: 0.76 (0.42-0.92) for SA, 0.89 (0.73-0.96) for CT and 0.96 (0.90-0.98) for ST.

**FIGURE 3.1.** The crossover turning (A) and sidestep turning (B) chair rises are illustrated. The 90-degree turns were initiated by a 60-degree step, as indicated by lines on the floor.
Ground reaction force (GRF) data of the right side served as control variables. Start of loading and toe-off determined stance time: 1.49 ± 0.25 seconds for SA, 1.60 ± 0.29 seconds for CT and 1.49 ± 0.32 seconds for ST. Vertical load during CT and ST was lower then during SA ($p < 0.001$ for both), suggesting the turning and straight ahead tasks were quite similar in their weightbearing demands (Table 3.1). Different ground rotational loads were associated with each turning task. More internal torque occurred during CT and more external torque occurred during ST ($p < 0.001$ for both, repeated measures one-way ANOVA model). Average ensembles of GRF internal and external torques for each condition are presented in Fig. 3.2.

**Analysis**

We compared peak tibial internal rotation, peak tibial external rotation and range of axial rotation (peak internal minus peak external rotation) during 100 percent of stance. A one factor repeated measures ANOVA with three levels was followed by pair wise comparisons. The levels included SA, CT and ST.

<table>
<thead>
<tr>
<th>Variables</th>
<th>SA</th>
<th>CT</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GRF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical force (N/kg)</td>
<td>11.11 ± 0.80</td>
<td>10.44 ± 0.45</td>
<td>9.93 ± 4.4</td>
</tr>
<tr>
<td>Peak internal moment (Nm/kg)</td>
<td>0.049 ± 0.021</td>
<td>0.075 ± 0.022</td>
<td>0.028 ± 0.030</td>
</tr>
<tr>
<td>Peak external moment (Nm/kg)</td>
<td>-0.012 ± 0.016</td>
<td>-0.009 ± 0.021</td>
<td>-0.046 ± 0.022</td>
</tr>
</tbody>
</table>

Positive values indicate an internal torque at force plate level; Negative values indicate an external torque.
RESULTS

The knee rotation angles during turning and straight ahead rising differed significantly (Table 3.2). Peak internal rotation during crossover turning was 14.2 degrees (at 96 percent of stance), versus 11.8 degrees during straight ahead rising (at 97 percent of stance). Peak external rotation during sidestep turning was –6.7 degrees (at 75 percent of stance), versus –1.7 degrees during straight ahead rising (at 28 percent of stance). As a result, the combined range of axial rotation for both turning tasks together was 20.9 degrees, versus 13.5 degrees during
straight ahead rising ($p<0.001$). Average ensembles of axial knee rotation angles expressed as a percentage of stance time for three trials over all subjects are presented in Fig. 3.3.

**DISCUSSION**

This study investigated axial knee rotation during stance of rising out of a chair with immediate turning sideward. The addition of a turning movement showed an increased range of axial knee rotation. This is due to a significant increase in internal and external tibial rotation angles during crossover- and sidestepping, respectively. Turning steps are present during all kinds of activities and from Glaister et al. we know, that they make up a considerable portion of steps taken during daily life walking.\(^{10}\) To our knowledge, turning maneuvers associated with

**TABLE 3.2.** Average ± S.D. peak kinematic variables during each task across stance.

<table>
<thead>
<tr>
<th>Variables</th>
<th>SA</th>
<th>CT</th>
<th>ST</th>
<th>p-Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak internal rotation (°)</td>
<td>11.8 ± 4.4</td>
<td>14.2 ± 4.3</td>
<td>3.2 ± 3.0</td>
<td>&lt; 0.001(^{a})</td>
</tr>
<tr>
<td>Peak external rotation (°)</td>
<td>-1.7 ± 1.8</td>
<td>-1.3 ± 1.5</td>
<td>-6.7 ± 7.3</td>
<td>&lt; 0.001(^{b})</td>
</tr>
<tr>
<td>Range of axial rotation (°)</td>
<td>13.5 ± 3.9</td>
<td>20.9 ± 7.9</td>
<td>&lt; 0.001(^{c})</td>
<td></td>
</tr>
</tbody>
</table>

Positive values indicate tibial internal rotation;
Negative values indicate tibial external rotation;
\(^{a}\) Results of the one-way repeated measures analysis of variance;
\(^{b}\) CT significantly different from SA;
\(^{c}\) ST significantly different from SA;
\(^{c}\) Combined range of rotation for CT and ST tasks together was significantly different from SA.
sitting up and down have not been studied before. From our study we now know, that these maneuvers induce a large range of axial rotation in the knee (20.9 degrees). Therefore, including this unique set of tasks may be useful in studies that aim to compare freedom of axial rotation in different designs of TKA.

An increase of knee rotation, as was found in our study, will be the result of a rotating moment at the knee. This moment, reflected by the GRF, can be expected to increase when the body turns accelerating towards the intended direction of gait. The GRF rotating moment in our study increased in the same direction as axial knee rotation did,
internally during CT and externally during ST. Though GRF moment is not the same as knee rotating moment, the results indicate a different load between the tasks. Amplitude of axial knee rotation, however, is not only dependent on passive restraints and rotational moments, but also on muscle and contact forces.\textsuperscript{27-28} Further study, including knee joint kinetics, would be needed to completely understand the mechanics associated with turning activities.

Both age and gender may influence freedom of knee motion. Males are known to have more knee torsional stiffness.\textsuperscript{29} Our objective was to increase range of axial rotation, so with a sample consisting of even more males than females, we believe there was no gender bias. With respect to age our results must be carefully interpreted, since subjects in this study were relatively young compared to the mean age of TKA candidates. Increased age is responsible for stiffening of the joint, due to a mechanism of increased activation of antagonist muscles, to compensate for reduced muscle strength and increased joint laxity.\textsuperscript{30} In the same way, patients with knee osteoarthritis also have significantly higher muscle coactivity than age-matched controls,\textsuperscript{31} although Boonstra et al. showed recovery of coordination in chair rising after TKA implantation.\textsuperscript{32} Likewise, in our experience, elder people after TKA performing this task do not appear to have large differences in motor control strategy.

In optoelectronic analysis of axial knee rotation, relative movement of skin markers to underlying bone hinders the use of external markers. Since soft tissue artifact is primarily a problem around the femur, Houck et al.\textsuperscript{17} developed a Femoral Tracking Device, which was validated with bone pin markers
over the first 85 percent of stance during walking. The new Femoral Epicondylar Frame we used was designed to have more press-fit fixation, aiming to reduce soft-tissue movement artifact during increased knee flexion. However, this remains to be validated by a study with either bone pins or fluoroscopy.

There is a need for studying turning activities in the field of TKA. Although participation in turning/cutting activities was comparable to control subjects in a study by Noble et al., many patients after TKA had difficulty in performing them.33 Mobile-bearings knee prostheses have been designed to maintain a more natural knee function and improve survival of the implant. However, no major kinematic differences have been found between mobile-bearing and fixed-bearing TKA so far.34 We have demonstrated that a turning maneuver significantly increases tibial internal and external rotation in normal knees. Whether axial rotation differs between mobile- and fixed-bearing replaced knees, in a task known to induce larger rotation angles, remains to be investigated.

CONCLUSION

The current study revealed, that more tibial internal rotation occurs during a crossover step turn and more external rotation occurs during a sidestep turn, while rising from a chair. These findings could be important in the assessment of kinematical differences between TKA designs.
ACKNOWLEDGEMENTS

This work was financially supported by an unrestricted grant from DePuy (Johnson & Johnson Medical, Amersfoort, the Netherlands) and Biomet (Dordrecht, the Netherlands).
REFERENCES


