Interlimb asymmetry during walking following unilateral total knee arthroplasty

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Abstract

Osteoarthritis is the most common disease of the joints, and joint replacement surgery is often performed on the major lower extremity joints to relieve pain and improve function. While total knee arthroplasty is successful in restoring some degree of function, there are concerns in relation to the progression of osteoarthritis in other lower limb joints. The purpose of this study was to determine the symmetry of interlimb loading, knee excursion and knee joint stiffness following unilateral total knee arthroplasty. The null hypotheses that vertical loading peak, loading rates, knee flexion excursion and knee flexion stiffness would be the same in the involved and uninvolved limbs after unilateral total knee arthroplasty were tested. Sixteen subjects (eight male and eight female) with previous total knee arthroplasty participated. Kinematic and kinetic data were collected bilaterally during overground walking using a seven camera motion capture system and two force platforms. Following recovery from unilateral total knee arthroplasty, peak vertical ground reaction force, loading rates, knee flexion stiffness and knee flexion excursion are similar in the involved and uninvolved limbs.

Keywords: Gait; Joint replacement; Knee; Ground reaction force; Symmetry

1. Introduction

Osteoarthritis is the most common joint disease, affecting over 20 million people in the US [1]. Joint replacement surgery is often performed on the major weight-bearing joints of the lower extremity to relieve pain and improve or maintain function. The frequency of total knee joint arthroplasty (TKA) has increased substantially in recent years, with an 81% increase being reported from 1990 to 2000 [2]. While total knee replacement is successful at reducing pain, and restoring some degree of function to the affected joint, there are some concerns in relation to the progression of osteoarthritis in other lower limb joints. Recent studies tracking individuals following a knee or hip replacement indicate that there is a pattern to the degeneration that follows the initial surgery. Shakoor et al. [3] found that osteoarthritis progressed in a non-random manner, with the uninvolved limb being affected significantly more often than the involved side. They suggested that this may be due to altered joint loading, such that the uninvolved side is loaded more than the side with the TKA. In fact, further work found higher knee loading during walking in the uninvolved limb, compared to the involved limb, in a group of patients who had a previous total hip replacement an average of 15 months previously [4]. Specifically, greater external peak knee extension and adduction moments and greater medial compartment load were found in the contralateral knee compared to the ipsilateral [4]. Other work has also indicated that total hip replacement patients load the uninvolved limb more than the involved one after recovery from surgery [5,6]. It has been hypothesized that the development and progression of osteoarthritis is related to increased joint loading [7]. Furthermore, secondary changes in gait patterns at the hip have been reported recently in patients with knee osteoarthritis [8]. Greater hip joint loading was found in the group with knee osteoarthritis, compared to matched
controls, which may lead to faster progression of osteoarthritis.

The mechanics of both lower extremities during walking following recovery from total knee replacement have not been well documented. However, reduced knee joint flexion during walking in the involved compared to the unininvolved knee following TKA has been shown recently [9]. Since lower extremity loading is related to joint stiffness [10], knee joint stiffness during the loading response may be important in terms of the progression of lower extremity joint deterioration. In particular, interlimb asymmetry may be a factor in the predictable progression of osteoarthritis in the unininvolved limb.

The purpose of this study was to determine the symmetry of interlimb loading and knee joint stiffness following unilateral TKA. The null hypothesis that there would be no difference in vertical loading peak and loading rates between limbs following unilateral total knee replacement was tested. Furthermore, the hypothesis that there would be no difference in knee flexion excursion or knee flexion stiffness during loading response was tested. Symmetry angle was used to provide a standardized indication of interlimb symmetry.

2. Methods

2.1. Subject details

The study included 16 subjects (8 male and 8 female; age 61 ± 7 years; height 1.71 ± 0.10 m; mass 87.48 ± 15.04 kg) who had undergone TKA previously (28 months; range 4–96 months). All subjects provided written informed consent prior to participation in this study. All procedures were approved by the Institution’s Human Subjects Review Board prior to commencing the study. Male and female participants were recruited from the local community via newspaper advertisements, flyers in senior and fitness centers, and word of mouth. Subjects were excluded if they were aged over 75 years or had a body mass index greater than or equal to 40 (extreme obesity) or were still receiving physical therapy or other treatment related to the TKA (considered not yet recovered from surgery). Additionally, participants were excluded if they had other lower extremity joints replaced; they had a history of rheumatoid arthritis; they had other previous or current lower extremity injuries or surgeries that may affect gait (e.g. joint fusion); they were unable to walk without additional aids (e.g. cane and walker); they are unable to provide informed consent or follow instructions.

2.2. Data collection

Lower extremity position data were collected at 120 Hz using a seven camera motion capture system (Vicon, Oxford Metrics, Oxford, UK). Markers were placed on both lower extremities to enable three-dimensional kinematics to be determined for the stance phase of walking. Two AMTI force platforms (AMTI Inc., Watertown, MA) synchronized with the motion capture system were used to collect ground reaction force data for consecutive steps at 1200 Hz. Walking velocity was monitored via two photocells linked to a timer.

Molded thermoplastic shells with four non-collinear markers attached were secured laterally on the proximal thighs and posterodistally on the shanks [11,12]. Three markers were attached to the heel of each foot to approximate rearfoot motion. Several additional markers were attached to the subject initially to define the anatomical coordinate systems and inertial parameters of each segment. These markers were removed following a standing calibration trial. Anatomical markers were placed over each greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, and the first and fifth metatarsal heads.

Subjects wore standard, neutral laboratory running sandals (Bite Footwear, Redmond, WA) and walked overground at their self-selected speed (group mean: 1.25 ± 0.17 m s⁻¹). Data were collected for single consecutive left and right stance phases as the subject contacted each force plate located in the center of the walkway. Five acceptable trials (within 5% of the mean speed of the individual) were collected. Trials in which the subject did not contact the force platforms cleanly or appeared to change their gait to target the force platform, as determined subjectively by the investigators, were discarded. Subjects performed practice trials to ensure that they could maintain a consistent walking speed and make contact with the force platforms without modifying their gait.

2.3. Data analysis

Data were processed in Visual 3D (C-Motion, Rockville, MD). Marker trajectories were low-pass filtered at 6 Hz and kinetic data were low-pass filtered at 50 Hz using fourth order Butterworth filters. Sagittal plane ankle and knee angles were resolved about a joint coordinate system using rigid body analysis [13]. The timing of the vertical loading peak was used to define the loading response period of interest: from foot strike to loading peak [14]. Kinetic data, used in the calculation of joint stiffness, were calculated using inverse dynamics and are expressed as net internal moments normalized to body mass and height. Ground reaction force variables (vertical instantaneous (ILR) and average loading rate (ALR), loading peak: GRFPK) were calculated using custom LabView (National Instruments Corporation, Austin, TX) programs. Loading rates were calculated between 20% and 80% of the period between footstrike and the loading peak. This portion of the curve was chosen as it is the most linear portion of the initial loading part of the curve. Average loading rate was calculated as the total change in force divided by the total change in time over this period. Instantaneous loading rate was the peak sample-to-sample loading rate occurring during this period.

Knee flexion excursion (KEXC) was calculated as knee flexion range of motion during loading response. Average knee flexion stiffness (KSTIF) was calculated as the change in joint moment divided by the change in joint angle [15] during the loading response. Knee stiffness was calculated from the peak knee flexion moment occurring just after footstrike to better reflect the stiffness of the joint during the eccentric part of the loading response. All variables were determined for each of five trials on each limb per subject, averaged within the limb and then averaged across involved and uninvolved limb groups. Paired t-tests were used to test for significant differences between involved and uninvolved limbs. An alpha level of 0.05 was chosen to indicate a significant difference. In addition, effect sizes were determined for all variables, to aid the interpretation of any differences found. Symmetry angle [16] was calculated for each variable to provide an indication of the level of interlimb
3. Results

All variables were similar in the involved and uninvolved limbs of the study participants after recovery from TKA (Table 1; Fig. 1). There were no significant differences between limbs. Effect size calculations also supported the similarity of the involved and uninvolved sides. There was no effect of side on loading rates (ALR 0.08; ILR 0.11) and only a small effect of side on vertical loading peak (0.33). Additionally, there were small effects of side on knee stiffness (0.43) and knee flexion excursion (0.35). These data support the null hypothesis that there is no difference in vertical loading peak and loading rates, knee stiffness and knee flexion excursion between limbs during walking after TKA.

Group mean symmetry angles were positive, reflecting the majority of subjects with higher values on the uninvolved side (although these values were not significantly higher). However, the standard deviations span both positive and negative values, indicating that symmetry angles were quite variable across the subject group, particularly in the two knee joint measures (Table 1).

4. Discussion

The purpose of this study was to determine whether there were interlimb differences in loading and knee mechanics asymmetry after unilateral TKA. The formula used was SA (\%) = (45° - \arctan(X_{inv}/X_{uninv})) / 90° \times 100. Positive symmetry angle indicates a higher value on the uninvolved side.

### Table 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Involved</th>
<th>Uninvolved</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRFPK (BW)</td>
<td>1.07 (0.09)</td>
<td>1.09 (0.07)</td>
</tr>
<tr>
<td>ALR (BW/s)</td>
<td>6.04 (2.09)</td>
<td>6.19 (1.78)</td>
</tr>
<tr>
<td>ILR (BW/s)</td>
<td>11.99 (3.93)</td>
<td>12.41 (3.82)</td>
</tr>
<tr>
<td>KSTIF</td>
<td>0.025 (0.012)</td>
<td>0.032 (0.017)</td>
</tr>
<tr>
<td>KEXC (Nm/(mass kg \times height m))</td>
<td>11.2 (4.9)</td>
<td>13.1 (6.2)</td>
</tr>
<tr>
<td>SA (%)</td>
<td>0.8 (2.3)</td>
<td>1.2 (9.5)</td>
</tr>
<tr>
<td>ES</td>
<td>0.33</td>
<td>0.08</td>
</tr>
</tbody>
</table>

GRFPK in BW; ALR, ILR in BW/s; KEXC in Nm/(kg \times m); KSTIF is change in normalized joint moment (Nm/(mass kg \times height m)) divided by change in joint angle (°); SA is symmetry angle (%); ES is effect size.

Fig. 1. Ensemble average curves for the involved and uninvolved limbs following recovery from total knee arthroplasty for (a) vertical ground reaction force; (b) knee flexion angle; (c) sagittal plane knee moment during the stance phase of walking. The loading response period is from footstrike to the ground reaction force loading peak (approximated by shaded area).
after unilateral TKA. Results suggest that both peak vertical ground reaction force and loading rates are similar in the involved and uninvolved limbs after recovery from TKA. This supports the null hypothesis of no difference in loading between sides and is contrary to expectations. Epidemiological evidence from Shakoor et al. [3] of a predictable progression of osteoarthritis in the uninvolved side after joint replacement surgery, coupled with the hypothesis that development and progression of osteoarthritis is loading-related [7] suggests that forces would be higher on the uninvolved side. Given the similarity in both the rate of application and peak value of vertical ground reaction force between sides, it may be the physiological response of the lower extremity during weight acceptance which predisposes the uninvolved side to joint deterioration.

Knee flexion excursion and knee stiffness during weight acceptance were also similar in both limbs. Again, this supported the null hypothesis and was contrary to expectations. The lack of asymmetry after recovery from unilateral TKA is different from the observation by Mizner and Snyder-Mackler [9] of a smaller knee flexion excursion in the involved limb compared to the uninvolved 3 months after surgery. The short time post-surgery in that study is in contrast to the average 28 months post-surgery in the present study. Direct comparisons between studies should be made with caution due to the effect on the absolute values calculated of differences in methodology; relative comparisons between studies are more robust. Mizner and Snyder-Mackler [9] reported knee flexion excursions of about 11° and 19° in the involved and uninvolved limbs, respectively. Given that values of 11° and 13° were found in the present study, it may be cautiously suggested that the uninvolved limb is tending towards the involved limb over time to reduce the interlimb asymmetry after TKA. However, it is uncertain whether differences between the studies are related directly to the longer recovery period in the present study. Only a longitudinal study with an extended follow-up period can absolutely determine the progression of interlimb asymmetry during recovery.

Given that the knee flexion excursion in the uninvolved limb is lower over 2 years after surgery in this study compared to 3 months post-surgery in a previous study [9], it may be suggested that performance is reduced over time. Reduced performance of the uninvolved limb after TKA, with it becoming more similar to the involved limb as time progresses, was unexpected. However, this phenomenon was first discussed by Walsh et al. [17] who considered it inappropriate to use the uninvolved limb for comparison to the involved limb to assess performance of the involved limb after TKA. They suggested that reduced activity secondary to osteoarthritis and the TKA surgery may impair the function of the uninvolved side. The combined results of Mizner and Snyder-Mackler [9] and the present study appear to support this suggestion. Comparing interlimb mechanics suggests that gait is becoming more symmetrical as recovery from TKA progresses. Generally, this would be considered to be a good sign. However, on closer evaluation it is apparent that the decrease in asymmetry did not occur as a result of improved knee flexion excursion in the involved limb, but via a reduction in knee flexion excursion in the uninvolved limb. Increasing interlimb symmetry may be a functional gait adaptation in this population. However, becoming more symmetrical by tending towards an abnormal gait bilaterally may be related to the predictable deterioration of the uninvolved limb found by Shakoor et al. [3]. Therefore, measurement of interlimb symmetry alone is insufficient to determine whether gait is normal, since the limbs could be symmetrically abnormal.

Limitations of the present study should be noted when interpreting the results presented. The sample tested included a relatively wide range of months since surgery. It is unclear whether gait continues to change at longer intervals post-surgery. However, there were no significant correlations between the variables of interest and the number of months post-surgery. Furthermore, the comparison between the present study and that of Mizner and Snyder-Mackler [9] should be interpreted with caution. Although similar methods were used to capture data, minor differences in data processing methods can affect the absolute angles obtained. To minimize this effect, excursions were compared, rather than absolute values of peak angles.

The lack of interlimb differences found in the present study, coupled with the observation that the limbs are probably symetrically abnormal, points to the need for further work comparing both the involved and uninvolved limbs after TKA to healthy age-matched control subjects. It would be worthwhile studying all of the lower extremity joints to examine whether compensations for altered knee mechanics occur elsewhere in the kinetic chain. Compensation in the secondary planes of motion should also be considered. This would indicate whether the reduced excursion found at the knee is a normal consequence of aging or an adapted gait pattern accommodating reduced knee excursion during gait in the prosthetic knee after TKA. If the gait pattern is shown to be adaptive, this would indicate the importance of achieving a more normal pattern of knee flexion-extension during gait in the involved knee after TKA. Focusing on this key gait deviation during rehabilitation may reduce the change in knee mechanics in the uninvolved limb, which may protect the uninvolved limb against its predictable deterioration following unilateral TKA.

5. Conclusion

Following recovery from unilateral total knee arthroplasty, peak vertical ground reaction force, loading rates, knee flexion stiffness and knee flexion excursion are similar in the involved and uninvolved limbs.
Conflict of interest

None.

References