Lower Limb Biomechanics in Individuals With Knee Osteoarthritis Before and After Total Knee Arthroplasty Surgery

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ABSTRACT

We investigated the biomechanical changes that occur in the lower limb following total knee arthroplasty (TKA). Lower limb joint kinematics and kinetics were evaluated in 32 patients before and 12 months following TKA and 28 age-matched controls. Analysis of variance with Bonferroni-adjusted post-hoc tests showed no significant changes in knee joint kinematics and kinetics following TKA despite significant improvements in pain and function. Significant increases in peak ankle plantarflexion and dorsiflexion moments and ankle power generation were observed which may be a compensatory response to impaired knee function to allow sufficient power generation for propulsion. Differences in knee gait parameters may arise as a result of the presence of osteoarthritis and mechanical changes associated with TKA as well as retention of the pre-surgery gait pattern.

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Total knee arthroplasty (TKA) is a common procedure for the management of knee osteoarthritis (OA) [1,2]. However, recent studies have indicated that despite experiencing significant reductions in pain, many TKA patients do not achieve normal joint function when walking following surgery [3–8]. In most cases, gait remains slower than asymptomatic controls, with the treated knee exhibiting abnormal biomechanics [6,8]. Moreover, abnormal pre-surgery gait has been reported to affect the post-surgery gait pattern, with many patients retaining their pre-surgery knee joint loading pattern [9,10].

While several gait changes specifically associated with knee function have been reported, only a few studies have attempted to capture how gait changes at joints proximal and distal to the knee due to abnormal knee function following TKA [5,11]. Oullet and Moffat [5] reported increased hip flexion and reduced ankle plantarflexion in 16 patients following TKA, which was suggested to be an adaptive strategy to compensate for the weak knee extensor muscles. Similarly, Mandeville et al [11] reported an increase in the hip moment contribution to total lower limb support in 21 patients following TKA compared to controls, suggesting that the hip may compensate for the diminished knee extensor contribution during walking [11]. These studies, however, had relatively small sample sizes and relatively short duration of follow-up (2 and 6 months, respectively). Moreover, assessment of other important gait parameters that provide information about muscle action and function, such as joint power, has yet to be thoroughly investigated following TKA. A more comprehensive biomechanical investigation during locomotion is needed to better understand the compensatory role of other joints of the lower limb following TKA.

Given the importance of maintaining adequate mobility in older people following TKA, identifying specific gait impairments following surgery may also help inform rehabilitation strategies. The purpose of this study, therefore, was to identify biomechanical changes in the lower limb in the sagittal plane following TKA. We hypothesised that altered gait function at the hip and ankle joints would be present following TKA to compensate for the impaired knee function.

Materials and Methods

Two groups of participants were recruited: a surgical group and an age-matched control group. This project was part of a larger study that investigated gait (swinging phase mechanics particularly minimum foot clearance), balance and falls risk in people before and after knee arthroplasty. A power calculation to determine the sample size, therefore, was based on minimum foot clearance parameters. Data from a previous study [12] which investigated the toe clearance of elderly fallers and non-fallers were used to determine the number of participants required. A sample size calculation indicated that for 80%
power and a \( P \) value of 0.05 at least 25 participants were required. To mitigate the possible effect of subject drop out for the surgical group, a total of 32 participants were considered to be sufficient.

The surgical group included 32 patients who were scheduled for TKA surgery and were tested prior to the surgery and at 12 months following their surgery. To be included in the study, participants needed to be able to walk at least 45 m independently, and potential participants were excluded if they had uncontrolled systemic disease or a pre-existing neurological or other orthopaedic condition affecting their ability to walk. Participants were recruited from the La Trobe University Medical Centre and the Warringal Private Medical Centre. Surgeries for the participants from the surgical group were performed by three experienced surgeons using the following prostheses: Scorpio NRG (Stryker, USA), Active TKR (ASDM, Australia), Triathlon (Stryker, USA) and Genesis II (Smith and Nephew, Hamburg/Schenefeld, Germany). The control group included 28 asymptomatic participants with no clinical diagnosis of OA, rheumatoid arthritis or history of knee trauma or pain. Participants from the control group were recruited from retirement villages in northern Melbourne and through newspaper advertisements. Ethics approval was obtained from the Faculty of Health Sciences Human Ethics Committee, La Trobe University. Participants were informed about the nature of the study and signed a consent form prior to participation.

Gait analysis was performed using a 3D motion analysis system (VICON, Oxford Metrics) with ten (MX3 and MX40) cameras operating at a sampling rate of 100 Hz. Two 1000-Hz force plates (Kistler, type 9865B, Winterthur, Switzerland and AMTI, OR6, USA) were used to capture ground reaction forces and identify gait cycle events. To assess motion, moments and powers of the hip, knee and ankle in the sagittal plane, retro-reflective markers were attached to anatomical landmarks in accordance with the Oxford Foot Model (OFM) marker set and Plug In Gait (PIG) as described by Stebbins et al. [13]. Prior to evaluation, a relaxed standing calibration trial was captured. Several markers, used only in the static trials, were removed prior to the dynamic trials as described in Stebbins et al. [13]. The locations of the joint centres were calculated from PIG and the OFM.

Participants attended the gait laboratory prior to undergoing TKA and at 12 months following the surgery, and function of the operated limb was assessed. No patients were lost to follow up. The control group was tested once and the instrumented leg was selected to match the proportion of left and right limbs evaluated in the surgical group. Participants were asked to walk at a comfortable walking pace along a 12 m walkway and five trials where the participant’s foot landed on the centre of the force plate without any interference to their gait were collected for each leg. For each trial, gait events were detected using vertical ground reaction force data to determine initial foot contact and toe off. Multiple trials were practiced until participants were comfortable and walking with consistent velocity. Peak values of interest of each trial were extracted separately and the average of the five trials was used in the analysis. Gait variables were normalised to the gait cycle and timing of peak angular variables was then expressed as a percentage of the gait cycle. Joint moments are expressed as a percentage of the gait cycle. Joint powers were normalised to body weight and are reported as Watt/kg (W/kg).

Knee Pain, Function and Stiffness

Physical function, pain and stiffness were assessed using the Western Ontario and McMaster University Osteoarthritis Index (WOMAC) [14]. This index, using 10 mm visual analogue scale, assesses the severity of the knee pain during 5 daily activities (range 0–500), stiffness (range 0–200), and the severity of impairment of lower-extremity function during 17 activities (0–1700). Zero score represents no pain or difficulty with physical function and higher scores represent worse functional health. All three subcategories are summed to give a global WOMAC score (range 0–2400). Pain during walking was also recorded on a 100 mm visual analog scale (VAS), where 0 represents no pain and 10 represents worst possible pain.

Data Analysis

Kinematics and kinetics of the hip, knee and ankle in the sagittal plane were analysed. More specifically, the following gait parameters were extracted: angle at initial contact and range of motion of all three joints, peak hip extension during stance, peak knee extension and knee flexion during stance, peak knee flexion during swing, peak ankle plantarflexion during early stance and late stance and peak dorsiflexion during push off. Joint moments in the sagittal plane included: peak hip flexion and extension moments, peak knee flexion and extension moments and peak dorsiflexion and plantarflexion moments. Joint powers included: hip power generation (H1), hip power absorption (H2), hip power generation (H3), knee peak power absorption at loading phase (K1), knee peak power generation (K2), peak knee power absorption late stance (K3), peak ankle power generation early stance (A1), peak ankle power absorption late stance (A2) and peak ankle power generation at push off (A3) (see Fig. 3). Spatio-temporal parameters of gait including gait velocity, stride length and cadence were also extracted.

Comparisons were made for all selected gait variables between the groups at baseline (control versus surgical group pre-operatively) and at 12 months (control versus surgical group post-operatively) and within the surgical group (pre-operatively versus post-operatively) using a mixed-design ANOVA, with one fixed factor (surgical or control group) and one repeated measure (pre-surgery and post-surgery gait pattern). Analysis of variance with Bonferroni-adjusted post-hoc tests was used to assess the differences for the gait variables with gait velocity entered as a covariate. Paired t-tests were used to compare differences in pain, stiffness and function (WOMAC scores) as well as the pain level during walking. T-tests were also used to explore the differences in the spatiotemporal parameters (gait velocity, stride length, cadence) between the groups. Data with skewed distributions were appropriately transformed prior to inferential parametric analysis. All statistical tests were conducted using SPSS version 17 for Windows (SPSS Inc, Chicago, IL).

Results

Participant characteristics are summarised in Table 1. No differences were found between the groups for age or height (Table 1), however the knee OA group had a significantly larger mean BMI (30.4 (5.1) vs 25.3 (4.5) kg/m²; \( P<0.001 \)). The surgical group walked significantly slower (1.13±0.19 m/s versus 1.37±0.17 m/s; \( P<0.001 \)) with shorter stride length (1.19±0.15 m versus 1.36±

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Participant Characteristics.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surgical Group (n=32)</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Gender % (n)</td>
<td>66.3 (6.4) F</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>167.7 (8.7)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>85.4 (12.7)</td>
</tr>
<tr>
<td>Body mass index (kg/height²)</td>
<td>30.4 (5.1)</td>
</tr>
</tbody>
</table>

Values are reported as mean±SD unless otherwise noted.

* Significant at \( P<0.05 \).
0.13 m; \( p < 0.001 \) and reduced cadence (113.76±8.44 steps/min versus 121.27±8.94; \( p = 0.002 \)) before surgery compared to the control group. The spatio-temporal parameters remained significantly lower at 12 months post-surgery compared to the control group (velocity 1.18±0.17 m/s, \( p = 0.654 \); stride length 1.23±0.16 m, \( p = 0.686 \); cadence 115.20±7.54 steps/min, \( p = 1.00 \)). Joint angular motion, joint moments and joint powers are presented in Figs. 1–3, respectively.

Significant improvements were found for pain (180.6±94.5 vs 152.1±251.3; \( p = 0.013 \)), stiffness (93.8±46.4 vs 32.4±37.9, \( p < 0.001 \)), function (594.6±315.0 vs 126.2±151.4, \( p < 0.001 \)) and the overall WOMAC score (869.2±409.2 vs 310.8±410.8; \( p < 0.001 \)) following the surgery, with a significant reduction in pain during walking (35.0±25.4 vs 6.9±15.1; \( p < 0.001 \)).

Within-Group Differences (Surgical Group Pre Versus Post)

No significant differences were found between pre-surgery and post-surgery for any of the hip measures. However, peak knee flexion moment, ankle plantarflexion and dorsiflexion moments and A3 power generation were significantly increased following surgery (Table 2).
The surgical group demonstrated greater ankle dorsiflexion before surgery and after surgery compared to the control group. Pre-surgery, the surgical group contacted the floor with a larger ankle dorsiflexion at initial contact compared to the control group. Larger peak power A1 was observed in the surgical group before surgery compared to the control group.

Following the surgery, the surgical group showed reduced peak knee extension motion, peak knee extension moment and peak K3 power absorption during stance compared to the control group. Significantly greater ankle dorsiflexion motion was also observed for the surgical group compared to the control group. No significant differences were observed at the hip joint pre and post-surgery compared to the control group (Table 2).

**Discussion**

Normal biomechanical function of the knee during walking may not be fully restored in people following TKA [6,8], and therefore compensation in other lower limb joints may occur. However, the mechanism causing gait changes in older people following TKA has been inadequately addressed, with most studies focusing on the knee joint only. In the present study, biomechanical changes at the knee and ankle joints were observed before and after surgery, highlighting the potential role the ankle joint plays in compensating for the impaired knee function before and following the surgery.

Generally, no significant changes in temporo-spatial parameters, knee joint kinematics and kinetics during gait were observed in the surgical group following surgery, despite improvements in pain and self-reported function. Only knee flexion moment significantly increased following the surgery. These findings are similar to previous studies that have shown that abnormal knee joint function may still be present following TKA [6,8] and those studies reporting substantial improvements in pain and mobility despite limited improvement in knee function following the surgery [15,16]. Consequently, it is unclear if patients continue to walk with a similar pattern that they had adopted before the surgery as previously suggested [3]. It may be possible that the abnormal gait observed following surgery is a result of a combination of the surgical intervention and retention of the pre-surgery gait pattern. Therefore, therapeutic strategies may be needed to focus on rehabilitation to improve knee function as well as gait retraining to optimise recovery following TKA.

Changes in ankle joint moments were observed following surgery, with increases in peak plantarflexion and dorsiflexion moments and A3 ankle power generation. It is possible that the ankle joint compensated for the impaired knee function to increase forward momentum and allow sufficient power generation for propulsion. Interestingly, the surgical group exhibited increased ankle dorsiflexion motion at late stance both before and after the surgery compared to the control group. Increased ankle dorsiflexion leads to lengthening of the calf musculature prior to push-off, which may contribute to the concentric force generation of the ankle muscles during push-off. Consequently, the increased ankle dorsiflexion may be a compensatory response to allow sufficient power generation at the ankle during propulsion. Indeed, increased calf muscle activation has been reported one year post-TKA, indicating greater force generation [17]. Increased ankle dorsiflexion may also compensate for the lack of knee extension observed in the surgical group during late stance before and after surgery compared to the control group, to assist in advancing the leg into swing and to propel the body forward (Fig. 1).

Studies investigating gait dysfunction in older people have focused on the premise that a loss of ankle joint power generation (A3) is responsible for gait changes such as reduced step length and walking speed [18–20]. Reduced ankle power generation during push off may limit forward progression of the body and diminish the momentum of the swing limb. Older people with impaired lower limb function, such as reduced knee flexion and extension, reduced peak power at initial contact and midstance, and reduced total knee range of motion, may be unable to maintain balance and propel the body forward. The results of these studies suggest that ankle dorsiflexion is an important factor in maintaining balance and propulsion during gait. However, the mechanism by which ankle dorsiflexion is linked to knee function remains unclear.

**Between-Group Differences (Control Versus Surgical Group, Pre-Surgery and Post-Surgery)**

Pre-surgery, the surgical group exhibited greater knee flexion at initial contact, reduced knee extension at midstance and reduced total knee range of motion in the sagittal plane, reduced knee extension moment as well as reduced K1, K2 and K3 peak powers (P<0.001) compared to the control group (Table 2).
### Table 2

Differences in Peak Joint Angles, Moments and Powers in the Surgical Group Between Pre-Surgery and Post-Surgery and Between the Control and the Surgical Group.

<table>
<thead>
<tr>
<th>Joint angles (°)</th>
<th>Pre-Surgery vs Post-Surgery</th>
<th>P Value</th>
<th>Pre-surgery vs Control</th>
<th>Post-Surgery vs Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgical Group</td>
<td>Post-Surgery Surgical Group</td>
<td></td>
<td>Control Group</td>
<td>P Value</td>
</tr>
<tr>
<td>Hip initial contact</td>
<td>36.42 (7.88)</td>
<td>&lt;1.00</td>
<td>35.18 (7.11)</td>
<td>1.00</td>
</tr>
<tr>
<td>Hip extension</td>
<td>−3.94 (8.99)</td>
<td>1.00</td>
<td>−11.15 (7.83)</td>
<td>0.254</td>
</tr>
<tr>
<td>Hip range of motion</td>
<td>41.75 (4.96)</td>
<td>&lt;1.00</td>
<td>46.51 (5.09)</td>
<td>1.00</td>
</tr>
<tr>
<td>Knee initial contact</td>
<td>14.13 (5.29)</td>
<td>0.494</td>
<td>9.82 (3.27)</td>
<td>0.005b</td>
</tr>
<tr>
<td>Knee flexion stance</td>
<td>22.43 (6.64)</td>
<td>0.961</td>
<td>20.96 (5.40)</td>
<td>0.781</td>
</tr>
<tr>
<td>Knee extension stance</td>
<td>11.16 (6.54)</td>
<td>0.651</td>
<td>1.83 (4.63)</td>
<td>&lt;0.001b</td>
</tr>
<tr>
<td>Knee flexion swing</td>
<td>57.86 (10.08)</td>
<td>1.00</td>
<td>61.07 (3.79)</td>
<td>1.00</td>
</tr>
<tr>
<td>Knee range of motion</td>
<td>47.74 (12.41)</td>
<td>0.302</td>
<td>59.24 (4.24)</td>
<td>0.002b</td>
</tr>
<tr>
<td>Ankle initial contact</td>
<td>1.39 (4.13)</td>
<td>0.616</td>
<td>−1.48 (3.16)</td>
<td>0.011b</td>
</tr>
<tr>
<td>Ankle plantarflexion ES</td>
<td>−3.64 (3.04)</td>
<td>0.673</td>
<td>−5.48 (2.47)</td>
<td>0.203</td>
</tr>
<tr>
<td>Ankle dorsiflexion</td>
<td>17.13 (2.84)</td>
<td>1.00</td>
<td>14.37 (2.58)</td>
<td>0.019b</td>
</tr>
<tr>
<td>Ankle plantarflexion LS</td>
<td>−10.52 (5.70)</td>
<td>1.00</td>
<td>−15.98 (6.17)</td>
<td>0.056</td>
</tr>
<tr>
<td>Ankle range of motion</td>
<td>27.65 (5.49)</td>
<td>1.00</td>
<td>30.36 (5.53)</td>
<td>0.838</td>
</tr>
</tbody>
</table>

### Peak joint moments (°BW*H)

<table>
<thead>
<tr>
<th>H1 power generation</th>
<th>Pre-Surgery</th>
<th>Post-Surgery</th>
<th>P Value</th>
<th>Control Group</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 power absorption</td>
<td>−0.53 (0.36)</td>
<td>−0.58±0.31</td>
<td>1.00</td>
<td>−0.89 (0.41)</td>
<td>0.786</td>
</tr>
<tr>
<td>H3 power generation</td>
<td>−1.44 (0.53)</td>
<td>1.63±0.49</td>
<td>0.001b</td>
<td>2.17 (0.63)</td>
<td>0.317</td>
</tr>
<tr>
<td>K1 power absorption</td>
<td>−0.43 (0.25)</td>
<td>−0.61±0.30</td>
<td>0.346</td>
<td>−0.91 (0.46)</td>
<td>0.018c</td>
</tr>
<tr>
<td>K2 power absorption</td>
<td>0.08 (10.10)</td>
<td>0.17±0.15</td>
<td>0.061</td>
<td>0.25 (0.17)</td>
<td>0.002b</td>
</tr>
<tr>
<td>K3 power absorption</td>
<td>−1.17 (0.58)</td>
<td>−1.09±0.40</td>
<td>0.077</td>
<td>−1.70 (0.43)</td>
<td>1.000</td>
</tr>
<tr>
<td>A1 power generation</td>
<td>0.65 (0.04)</td>
<td>0.11±0.07</td>
<td>0.165</td>
<td>0.18 (0.13)</td>
<td>0.035b</td>
</tr>
<tr>
<td>A2 power absorption</td>
<td>−0.69 (0.21)</td>
<td>−0.76±0.18</td>
<td>0.885</td>
<td>−0.74 (0.25)</td>
<td>1.000</td>
</tr>
<tr>
<td>A3 power generation</td>
<td>2.80 (0.87)</td>
<td>3.70±0.98</td>
<td>&lt;0.001c</td>
<td>4.06 (0.84)</td>
<td>0.086</td>
</tr>
</tbody>
</table>

Abbreviations: ES, early stance; LS, late stance.

- a Significant differences for the surgical group between pre-surgery and post-surgery.
- b Significant differences between the surgical group pre-surgery and the control group.
- c Significant differences between the surgical group post-surgery and the control group.

As those with knee OA have been shown to have reduced ankle power generation, even after adjusting for gait velocity [21,22]. Interestingly, Ko et al [22] reported a reduction in ankle generative mechanical work expenditure in asymptomatic knee OA participants (who reported no pain) compared to asymptomatic controls while no differences were observed between symptomatic knee OA participants and the control group. Given that the present knee OA group was at end-stage OA, with severe characteristic structural changes and clinical symptoms, the gait changes observed may have been adopted over time in an attempt to offload the knee and reduce pain. A compensatory response to decreased ankle power generation is often observed at the hip, where an increase in hip flexor power (H3) occurs [23]. However, gait changes at the hip were not evident in the surgical group in contrast to previous reports [5,11]. The differences between these studies and the present study may be related to the different time of follow up. Mandeville et al and Ouellet and Moffet have tested the participants relatively early after TKA (2 and 6 months post-surgery) while improvement in locomotor deficit is expected to occur during the first year following the surgery. Hip flexion contracture and/or limited hip extension is common in older people and result in reduced step length and gait velocity [19,24,25]. Similarly, ankle power generation can be affected by limited hip extension, as it does not allow the lower leg to be positioned in an orientation that facilitates ankle plantarflexion. However, it is unclear if proximal or distal joint gait alterations are a cause or a consequence of reduced gait velocity. Interestingly, gait differences at the hip or ankle, in the present study; appear to be velocity-dependent, as when velocity was entered as a covariate, differences between the groups were not evident (data not shown). Moreover, given that no differences were found in ankle power generation between the groups, suggesting that ankle muscles were able to function sufficiently to advance the body forward, additional support from the hip may not have been required. Since walking ability is important for independent function of older people, improving walking performance following TKA may require exercise rehabilitation to increase hip and ankle strength [26] in addition to exercises targeting the knee.

Pre-surgery, the surgical group contacted the ground with greater knee flexion, reduced knee extension motion during stance and reduced total knee range of motion compared to the control group, similar to previous reports [27,28]. Moreover, peak knee powers K1 and K2 were also significantly lower for the surgical group, which may be due to a reduced capacity of the knee extensors to generate muscle power through eccentric contraction during the loading phase at K1 and concentric contraction at midstance during K2. This may be further supported by the reduced knee extension motion and knee extension moment during mid stance. Given that knee OA has been shown to be associated with reduced muscle strength [29,30], particularly of the quadriceps, those findings may be interpreted as reflecting muscle weakness during gait.

Following the surgery, peak knee extension motion and peak knee extension moment remained lower compared to the control group, consistent with previous reports [4,31]. The flexion/extension moment gait pattern of the surgical group as seen in Fig. 2 may indicate a tendency for knee flexion moment pattern, where the knee is more flexed throughout the gait cycle, which is commonly observed following TKA [4,10,32]. A significant reduction in peak knee power absorption K3 during late stance was also demonstrated in the
surgical group post-surgery compared to the control group (Fig. 3). Reduction of K3 may suggest impaired function of the quadriceps during pre-swing in controlling knee flexion and may be related to altered quadriceps muscle function reported following TKA [17]. Another possible explanation for these findings may be related to the muscle activation pattern of the hamstring and quadriceps following TKA, as muscular co-contraction around the knee has been suggested to be a compensatory mechanism to provide greater control and stability of the knee during the stance phase [33]. Consequently, the changes observed at the knee may be related to the mechanical changes associated with the surgical intervention such as soft tissue tension, passive joint stability, neuromuscular adaptation [17] and amount of swelling around the knee joint [34].

The present study has several limitations, particularly with regard to the study population. Although the control and the surgical groups were similar in age, differences in weight and BMI were evident. The surgical group was heavier, which could have affected some of the gait measures. To account for such differences, all kinetic parameters were normalised to the participants’ body mass and height. Moreover, while our results show gait changes at self-selected walking speed, there is a need to investigate gait changes when performing more challenging gait tasks, such as fast walking [22], that require greater joint loading. It is also important to acknowledge that various knee designs may affect gait patterns, however the precise effect on knee biomechanics is unclear and remains an ongoing debate in the literature [3,34–38].

Conclusion

Several biomechanical changes in the knee and ankle were identified in the surgical group before and following TKA compared to the control group. Differences in gait parameters observed at the knee may arise as a result of the presence of OA and mechanical changes associated with TKA as well as retention of the pre-surgery gait pattern. Consequently, the gait alterations observed at the ankle joint may be a compensatory response to facilitate forward momentum and allow sufficient power generation for propulsion. Rehabilitation strategies may therefore need to focus not only on improving knee function, but also on gait retraining to optimise recovery following TKA.

Acknowledgment

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References
