Joint Stiffness of the Ankle during Walking after Successful Mobile-Bearing Total Ankle Replacement

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Abstract

Introduction It has been shown that walking kinematics remain near to normal after mobile bearing total ankle replacement (TAR). However, no information is available on mechanical joint loading. The purpose of this study was to determine whether mechanical load and ‘quasi-stiffness’ of the ankle joint after TAR differs from the normal load and stiffness of a healthy ankle joint during walking.

Methods Ten TAR patients and 10 age-matched healthy control subjects (CO) participated in this study. Participants walked barefooted on an indoor track of approximately 8 meters at self-selected walking speed. 3D ankle kinematics and ground reaction forces were measured and used for the calculation of 3D net joint moments, joint quasi-stiffness coefficients and internal net joint ankle work.

Results Between patients and control subjects no differences were observed in peak moments and stiffness coefficient at the ankle. Internal work at the ankle during the step differed however, significantly (-0.078 (0.088) vs. 0.005 (0.048) J·kg⁻¹ for TAR vs. CO, p=0.02), although it could be argued that this difference was due to a minor difference in walking speed between both groups (1.02 (0.07) vs. 1.09 (0.07) for TAR vs. CO, p=0.02).

Conclusion Despite the small difference in internal work at the ankle, it could not be concluded that the mechanical loading of the ankle after TAR differed from normal.

Keywords: Ankle; Arthroplasty; Gait; Joint Stiffness; Joint Moment
9.1 Introduction

For painful arthritic ankle joints a mobile-bearing total ankle replacement (TAR) is a treatment option. In contrast to its alternative, an ankle arthrodesis, TAR preserves joint motion. This might prevent secondary overuse in the adjacent joints of the foot, which show compensatory motion in the case of an arthrodesis. Literature on the success of mobile-bearing TAR describes varying, though generally good results. In a recent study we described the 3D kinematic pattern in ten patients after TAR and compared this to a control group. Although patients had a reduced range of motion in the ankle during clinical mobility testing, no effect on the functional range of motion during walking was found. The EMG patterns, however, showed more co-contraction of the anterior tibial muscle and gastrocnemius and soleus muscles during midstance in the patient group. Muscle co-contraction increases the internal joint reaction forces and the mechanical stress on the endo-prosthesis. This might indicate that, despite the kinematic similarities, the mechanical behavior of the replaced ankle is different compared to the healthy ankle.

The mechanical load of body joints can be analyzed in terms of net joint moments. However, net joint moments are unsuitable for the estimation of the effect of co-contraction on the internal joint loading. The net joint moment remains unchanged irrespective of the degree of co-contraction. An alternative procedure for analyzing the mechanical behavior of the joint, including the effect of co-contraction is to calculate the dynamic joint stiffness. Dynamic joint stiffness can be defined as the resistance that a joint (i.e. the muscles and other soft tissue structures that cross the joint) offers during gait in response to an applied angular displacement. It should be noted however, as Latash and Zatsiorsky argue, that joint stiffness does not necessarily imply that the tissue around the joint behaves as a physical spring, storing and releasing energy. Latash and Zatsiorsky therefore define this behavior of the joint as 'quasi-stiffness'. Joint quasi-stiffness can be an important determinant of stress generation in the joint, since joint quasi-stiffness depends heavily on and is therefore indicative of the degree of muscle co-contraction.

A relatively simple method for estimating joint quasi-stiffness is to examine the relation between the net moment at the ankle joint versus the angular displacement of the ankle. This quantity (the quasi-stiffness coefficient) can reveal the overall mechanical system behavior of the joint (and hence joint stress) during the stance phase of walking, as was demonstrated previously.

So far the ankle joint kinetics and stiffness in a 3D model in patients after TAR have not been examined. Dyrby et al. investigated 2D net joint moments in nine patients using the STAR prosthesis but did not look at possible co-contraction.
and joint quasi-stiffness. The goal of the present study was to determine whether quasi-stiffness and mechanical load of the ankle joint after arthroplasty differs from the normal stiffness and load of a healthy ankle joint during walking. To investigate this, we analyzed 3D net joint moments and quasi-stiffness of the ankle joint of TAR patients and compared these to a group of age- and gender-matched control subjects.

9.2 Materials and Methods

9.2.1 Subjects
Ten post TAR patients and a group of ten healthy control subjects, matched for age and gender participated in this study. The ten patients, six males and four females, had received a unilateral mobile-bearing total ankle replacement using the Buechel-Pappas prosthesis\textsuperscript{14}. Five replacements had been carried out for posttraumatic arthritis and five for rheumatoid arthritis. The mean time from surgery was 41.5 months (range 11-126 months). The study was approved by the local medical ethics committee. Prior to testing, subjects were informed about the aims and procedure of the experiment, after which they gave informed consent. After completing the measurement, an explanation of the expected results was given.

To reduce possible bias from co-morbidity the inclusion criteria for the patients were (1) that they had their joint replaced at least 10 months earlier and (2) that they should have a minimum ankle score of 80 points on both the LCS\textsuperscript{15} and the AOFAS\textsuperscript{16} scoring systems. In this way, patients with pain and a reduced function for whatever reason were excluded.

The sample size of ten subjects in each group was found to be sufficient to reveal a clinically relevant difference for peak moment and joint stiffness of 10\% and 15\% respectively, using a power calculation with alpha 0.05, beta 0.50, and the standard deviations as derived from the first five participants in each group.

9.2.2 Data Acquisition and Testing Procedures
The laboratory gait evaluation included the simultaneous recordings of body kinematics and ground reaction forces in subjects walking at their self-selected speed. To measure 3-D kinematics an opto-electronic motion analysis system (Optotrak: Northern Digital Inc., Canada), including 4 units with each 3 cameras, was used. Marker placement followed the protocol described earlier by Wu et al.\textsuperscript{1}. This protocol was chosen instead of the ISB recommendations\textsuperscript{17}, since it was used in a previously reported part of this study\textsuperscript{7} comparing kinematics after TAR with a group of patients after ankle arthrodesis reported by Wu et al.\textsuperscript{1}. The accuracy and repeatability of this
Joint stiffness of the ankle during walking after successful mobile-bearing TAR protocol was assessed by Wu et al.\(^1\) and found to be satisfactory. In short, markers on the tibio-fibular segment were placed on the lateral and medial tibial condyles and lateral and medial malleoli. On the hindfoot segment, markers were placed on the lateral, posterior and medial calcaneus. One additional marker, placed at the pelvis was used to measure walking speed. Data were collected at a sampling rate of 100 Hz.

One Kistler force plate (Type 9281A11, Kistler Instrument Corp., Winterthur, Switzerland, dimensions 0.60 x 0.40 m) was synchronized with the Optotrak system to measure ground reaction forces (GRF) and the center of pressure (CoP). Data were sampled at a rate of 100 Hz. The ground reaction force was recorded on the operated side for the patients and on the right side for the control subjects. When the operated leg was the left one, data were mirrored to the right during the data analysis procedures.

After marker placement, subjects were asked to walk barefoot forward on a flat 8 m walkway, in which the force plate was incorporated. Before data collection started, subjects walked on the walkway several times until they indicated they were familiar with the walking conditions. Data from a minimum of three gait cycles were collected for each subject walking at his/her self-selected speed. When more than three successful runs were obtained, the three with the most closely matching walking speed were selected.

### 9.2.3 Data Analysis

The ankle angle was defined as the orientation of the hindfoot relative to the orientation of the local coordinate systems of the tibio-fibular segment. In the local tibio-fibular segment frame, first the x-axis (plantar-dorsal flexion) was fixed between both malleoli; subsequently, the y-axis (ab-adduction) was orientated perpendicular to the x-axis and a line from the midpoint between both malleoli and the midpoint between both tibial condyles; and finally the z-axis (internal-external rotation) was orientated perpendicular to the x and y-axis. Ankle angle was expressed following the standard decomposition order: dorsiflexion–plantarflexion, abduction–adduction and internal–external rotation\(^1,7\). The anatomical zero of the ankle angle was defined to occur at 15 per cent of the gait cycle.

The 3D internal ankle net joint moment was calculated from the cross product of the ground reaction force and the distance between the CoP and the ankle center of rotation. The center of rotation of the ankle was chosen midway between the malleoli. The ankle moment was decomposed relative to the orientation of the local segment frame of the tibio-fibular segment. The local net ankle joint moments were presented as a percentage of the stance phase during the gait cycle and the amplitude was normalized to bodyweight. Peak values of the ankle moments around
the 3 orthogonal axes of the tibia segment were quantified.

Ankle joint quasi-stiffness around the plantar-dorsal flexion axis (the primary axis of rotation) can be observed as the slope of the ankle plantar-dorsal flexion net joint moment plotted as a function of angular displacement around this axis. In accordance with Davis and DeLuca\textsuperscript{8}, we calculated the quasi-stiffness coefficient from the slope of the linear regression of joint moment versus angular displacement during the second rocker interval of the stance phase, i.e. the period from the first relative maximum plantar flexion in early stance to maximum dorsiflexion in midstance. The net internal work (W\textsubscript{net}) generated at the ankle during stance was estimated by determining the area under the ankle moment versus ankle angle curve, according to:

\[ W_{\text{net}} = \int M_x \, d\phi_x, \quad (1) \]

Where \( M_z \) is the ankle joint moment around the plantar-dorsiflexion axis and \( \phi_z \) is the ankle angular displacement around this axis. The integral in Eq. (1) was computed using trapezoidal approximation\textsuperscript{10}.

9.2.4 Statistics
The data were tested for normality using the Kolmogorov-Smirnov test, which indicated that the outcome parameters did not deviate from a normal distribution. Hence, statistical analyses between the patients with ankle arthroplasty and the control subjects were undertaken using the two-tailed independent t-test to compare walking speed, peak joint moments, ankle quasi-stiffness and net internal work.

9.3 Results

9.3.1 Analysis of the Gait Pattern
Subjects were asked to walk at a self-selected comfortable walking speed. As it can be observed in Table 1, the TAR patient group walked approximately 6 per cent slower compared to the control group (p=0.02).
No significant differences were observed between groups in peak net joint moments generated at the ankle (Table 2, Figure 1). However, small differences in joint moments at the onset of the stance phase during the period of initial contact and loading response are presented in Fig. 1, where the average joint moments of the TAR-group exceeded the bandwidth (mean ± 1 SD) of the control group.

**Fig. 1** Internal ankle net joint moments of TAR patient group (solid thick line = mean, solid thin lines = mean ± 1 SD) in comparison with control group (shaded area = mean ± 1 SD).
The average ankle joint moment versus angular displacement around the plantar-dorsal flexion axis for both the TAR and control group is plotted in Fig. 2. There were no significant differences in the quasi-stiffness coefficient between the patient and the control group (Table 3). However, hysteresis of the angle-moment curve appeared to be different between the two groups. The angle-moment curve for the TAR patient group moved in a clockwise rotation, which implies that energy is dissipated around the ankle of the TAR patients during walking. In contrast, the angle-moment curve of the control group showed hardly any hysteresis. Indeed, the net work generated at the ankle during stance in the TAR group was significantly lower than in the control group (Table 3). Energy was dissipated at the ankle in the TAR group while the in the control group energy production at the ankle was, on average, close to zero.

**TABLE 2**  Peak net ankle joint moments (mean, SD) in Nm·kg⁻¹

<table>
<thead>
<tr>
<th></th>
<th>TAR</th>
<th>Control</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantar-dorsiflexion</td>
<td>1.38 (0.18)</td>
<td>1.43 (0.13)</td>
<td>0.26</td>
</tr>
<tr>
<td>Ab- adduction</td>
<td>-0.28 (0.13)</td>
<td>-0.20 (0.23)</td>
<td>0.36</td>
</tr>
<tr>
<td>Internal-external rotation</td>
<td>0.22 (0.17)</td>
<td>0.30 (0.14)</td>
<td>0.31</td>
</tr>
</tbody>
</table>

*Fig. 2* Ankle joint moment versus ankle angular displacement graph for TAR patients (dashed) and control subjects (solid). Stiffness coefficient was calculated as the slope during the second rocker interval of the stance phase, i.e. the period from the first relative maximum plantar flexion (negative) in early stance to maximum dorsiflexion (positive) in midstance. Net joint work can be observed as the area enclosed by the curves.
9.4 Discussion

In this study the quasi-stiffness and mechanical load of the ankle joint during walking was compared between a group of patients after a successful total ankle arthroplasty and a group of healthy gender and age-matched controls. Between these groups no significant differences were observed in the peak net ankle joint moment and quasi-stiffness of the ankle.

The equal peak plantar-dorsiflexion moment between groups in this study is in accordance with the results of Dyrby et al.13. However, these authors found a significant reduction in the abduction moment of the TAR group, which was not the case in our results. Ab-adduction moments are, however, difficult to compare between both studies since Dyrby et al.13 used a frontal-plane 2D approach to analyze these moments. Despite equal peak moments between groups, the pattern of the net joint moments in our study differed a little between TAR patients and the control group during the first 20 per cent of the stance phase. This could suggest that the patient group walked with a less pronounced heel landing than the control group. This walking pattern, however, did not alter peak joint moments.

We analyzed joint quasi-stiffness in addition to the net joint moments, since net joint moments do not reflect the effect of co-contraction of muscles around a joint. In contrast, joint quasi-stiffness would increase with increasing co-contraction9 and hence would be indicative of extra joint loading due to co-contraction. In our results we did not find a significant difference in ankle joint quasi-stiffness. This implies that, for this patient population and control group, differences in stiffness were absent or undetectable. Although the sample size in this study was low (and hence statistical power was somewhat low), the observed differences in peak plantar-dorsal flexion moment and stiffness between groups did not exceed 10 per cent and most patients fell within the range of values attained by the control group and within normal values reported in literature8,11,12. Hence, while increasing the sample size could result in significant differences, these differences do not seem clinically relevant.

Although there was no significant difference in the stiffness coefficient, the
ankles in the TAR patient group were shown to dissipate energy while the ankles in the control group were not dissipating energy. Several explanations could be postulated to account for this difference. First, this energy dissipation in the replaced ankles could have been caused by an increased internal friction of the joint, which would be indicative for joint wear. However, the definition of joint quasi-stiffness\(^9\) does not imply that the ankle would behave as a simple (damped) physical spring. Thus it is not possible to discern what structures, in and around the joint (i.e. joint surface, capsule/ligaments or muscles), would be responsible for energy generation and/or dissipation. The net negative joint work at the ankle could also indicate that the calf muscles of TAR patients may be affected by the ankle joint disease. They may be atrophic or patients may choose to protect their affected leg. In that case, the role of the calf muscles as power generators during walking would be replaced by other muscle groups, i.e. ipsilateral hip extensors or the contra-lateral leg. A third and perhaps most likely explanation for the difference in internal joint work may be related to the difference in walking speed between patients and controls. In the current study we have chosen to allow our subjects walk at their self-selected walking speed. However, the self-selected speed was different in the two groups. Hansen et al.\(^{10}\) showed that the hysteresis loop of the ankle angle-moment curves changed from clockwise (net energy dissipation) to counter-clockwise (net energy generation) with increasing walking speed and intersected at zero net joint work at approximately 1.3 m·s\(^{-1}\). Palmer\(^{18}\) found a similar crossover speed of 0.9 m·s\(^{-1}\). Our patient group had a mean walking speed of 1.02 m·s\(^{-1}\) while the control group had a mean walking speed of 1.09 m·s\(^{-1}\). The possible crossover speed from clockwise to counter-clockwise of our study (approximately 1.1 m·s\(^{-1}\)), hence, lies in the range that was found in earlier studies. Thus, the difference in net energy generation could well be explained by a difference in walking speed between the two groups.

Finally, it should be acknowledged that we have chosen to include only successful TAR patients with AOFAS and LCS scores above 80. This was done to exclude patients with co-morbidities around the foot and ankle and with complications after TAR surgery. These co-morbidities and complications would affect the walking pattern and hence obscure the effects of TAR in itself. Hence, this study investigated the mechanical behavior of the ankle after successful TAR surgery and generalization of the results to other populations should be considered with care.

In conclusion, this study showed that the mechanical load of the ankle joint during walking after successful total ankle replacement does not differ from the mechanical load of the healthy human ankle joint. Peak net joint moments and joint quasi-stiffness do not differ, and the difference in net joint work could be attributed to difference in walking speed. These findings indicate that the function of the ankle joint in terms of mechanical load and stiffness appears not to be influenced by total ankle replacement.
References


