The effect of proximal tibial corrective osteotomy on menisci, tibia and tarsal bones: a finite element model study of tibia vara

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Abstract

Background  Proximal tibial open wedge osteotomy (PTO) is a corrective operation used in the surgery of lower extremities and is applied to patients with varus deformities for sufficient correction. The aim of the study was to evaluate whether the PTO can achieve decreased stress-bearing on the tibia and tarsal bones in addition to correcting the mechanical axis of the lower limb in patients with tibia vara.

Methods  Three-dimensional (3D) solid modelling of the lower extremity was carried out using computed tomography (CT) and magnetic resonance (MR)-containing images of all of the bony elements and non-bony structures. PTO was applied to the obtained deformed model in the computer environment and the correction was carried out.

Results  Stress distributions in menisci, tibia and tarsal bones were calculated. With respect to loading on the tarsal bones, the maximum equivalent stresses on all bones decreased except for the navicula in the PTO-simulated model in the current study.

Conclusion  These results clearly indicate that PTO can achieve decreased stresses on the tarsal bones in patients with tibia vara. Copyright © 2013 John Wiley & Sons, Ltd.

Keywords  open wedge osteotomy; tibia; talus; finite elements method; computed tomography

Introduction

In terms of walking comfort and knee joint stabilization, the mechanical axis should be located between the femoral head globe and the distal end of tibia in a vertical position passing through the centre of the knee joint. Varus deformity, which is a tibial deformity, affects the function of walking, as it affects the load charged on the cruciate ligaments. Tibia vara is the most common cause of the pathological genu varum among children and adolescents; it is a progressive disease because of arrest of the medial proximal tibial epiphysis. The former is the result of excessive load on the medial half of the distal femoral epiphysis, while the latter is a compensatory deformity to the severe proximal tibial varus (1,2).

The aim of surgery is to relieve pain and correct limb alignment, with a horizontal knee joint for weight-bearing to prevent cartilage degeneration. Corrective osteotomies of the tibia for genu varum are well documented in...
the literature (1,4–8). The ideal osteotomy should be that which: completely corrects or over-corrects the deformity; is near the site of the deformity; is done in primarily cancellous bone; allows early motion of the knee and early weight bearing; provides convenience for exploration of the knee during osteotomy if it is indicated; and presents no undue technical difficulties or potential hazards (9).

We hypothesized that the proximal tibial open wedge corrective osteotomy (PTO) could achieve decreased stress-bearing on the tibia and tarsal bones in addition to correcting the mechanical axis of the lower limb in patients with tibia vara. In this study we evaluated the maximum equivalent stresses (MES) on the menisci, tibia and tarsal bones of a patient with tibia vara before and after the surgery, using a finite elements model study.

Materials and methods

3D modelling of lower extremity structures

In the field of medicine, computer-aided planning has frequently been used in recent years before surgical operations, conducted through such imaging techniques as computed tomography (CT) and magnetic resonance imaging (MRI). In this study, the main model was also modelled via CT images. CT images of the lower extremity bones were obtained from a female patient aged 21 using a Toshiba Aquilion CT scanner in the Department of Radiology of the Faculty of Medicine in Kocaeli University. CT images consist of parallel layers having a section range of 0.774 mm at the neutral position and a pixel resolution of 512 × 512. A 1841-layer shooting was carried out to develop the model used as reference. Images were recorded in the Digital Imaging and Communications in Medicine (DICOM) format. These images were then transferred to the MIMICS 12.11 program, which is 3D image-processing software.

PTO was completed digitally in the computer environment through the MIMICS program and a PTO tibia model was obtained. All bone structure models and geometric arrangements were completed through a reverse-engineering program (GEOMAGIC). After correction of the surface errors of the deformed and corrected models, 3D smooth solid models were developed. After geometric arrangements of the models were complete, finite elements models were obtained by transferring them into the MIMICS finite elements analysis (FEA) module content in stereolithography (STL) format.

Calculation of stress distribution

To compare the stress distributions observed in menisci, tibia and finite elements models of deformed and corrected lower extremities were transferred into ANSYS WORKBENCH (WB) software through the MIMICS FEA interface. Ten-node tetrahedral elements were used to form the mesh of the finite elements models. Computer-aided finite elements analysis aimed at comparing the stress distributions was carried out through ANSYS WB software.

Material properties of bone and non-bone structures

In this study, it was assumed that bone structures in the developed models were elastic and isotropic. Furthermore, the viscoelastic material properties of the bone structure were identified. Identification of viscoelastic properties of the bone structure in ANSYS WORKBENCH material editor was carried out by entering the bulk module 2.3 GPa (10,11) and the shear module (10–13). The material properties of bones, cartilage and menisci were identified by taking the values into consideration, as shown in Table 1.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Elastic modulus (E, MPa)</th>
<th>Poisson ratio (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibia</td>
<td>14,000</td>
<td>0.3</td>
</tr>
<tr>
<td>Femur</td>
<td>17,000</td>
<td>0.3</td>
</tr>
<tr>
<td>Meniscus</td>
<td>59</td>
<td>0.49</td>
</tr>
<tr>
<td>Cartilage</td>
<td>5</td>
<td>0.46</td>
</tr>
<tr>
<td>Tarsal bones</td>
<td>5000</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Boundary and loading conditions

The load exerted on the foot bones changes depending on the movement of a human body and the standing position. The fact that the load exerted by the body is transferred through the hip and knee joints was taken into consideration to calculate the stress-carrying capacities of the elements forming the lower extremity. In the study conducted by Simoes et al. (15) on different loads, such as muscle loads affecting the body weight and proximal femur, body burden was identified as 700 N and the abductor force was identified as 300 N. On the other hand, in the study carried out by Moreo et al. (16), the body burden used was 2092 N and the abductor force 975 N. Considering all these data, a body weight of 1000 N was applied to the surface of the femoral head globe in contact with the hip joint. As a component of the muscle loads, the abductor load exerted toward the pelvis through the trochanter major of femur was 500 N.

Due to the normal movement axis of the muscles and ligaments, a degree of freedom was identified to the femoral bone only in line with the mechanical axis. The surfaces of calcaneus and the other foot bones in contact with the ground were completely stabilized (zero displacement). The same loading and boundary conditions were determined in both models. A 10-node tetra-element was used for the finite elements models, obtained by giving importance to above-mentioned material properties and loading and boundary conditions, and these models contained...
242,235 elements on average. Additionally, bonded structures for the contacts of bone and cartilage structures with one another, contacts of the menisci on the tibial cartilage, and frictionless contact between the menisci and the femoral cartilage were identified separately. Stress distributions on the tibia, talus, calcaneus, navicula, cuboid, cuneiforms and medial and lateral menisci of the tibial varus model before PTO, and of the model corrected with PTO surgery, were compared.

Results

As shown in Figure 1, the highest equivalent stress in the model of tibia and foot bones of the patient with varus disease was about 56.9 MPa, while the highest stress was determined as 32.1 MPa in the model to which computer-assisted virtual PTO was applied. In terms of the stress values obtained from the tibiae of both models, more stress was recorded in the PTO model, with a value of 21.8 MPa when compared to the deformed model, whose degree of stress was measured as 16.3 MPa (Figure 2). Stress distributions on the menisci and tarsal bones before and after PTO are given in Table 2. Following PTO, a stress increase was recorded only on the navicula, which is the bone located in the middle of the foot. MES on the menisci were almost equal in both the medial and lateral meniscus in the deformed model; however, after PTO surgery, MES on the medial meniscus decreased, while it increased on the lateral meniscus (Table 2).

Discussion

As PTO surgery is frequently used in correction of tibial deformities, it is of great importance to compare the postoperative stress distributions with the preoperative results. In this study, the PTO technique was applied on the virtual platform and a computer-aided finite elements approach was used to explain both the preoperative and postoperative models. According to the results obtained, tibia vara was corrected and stress distributions on the foot bones and menisci were successfully determined through computer-aided finite elements models.

Varus deformity can usually be corrected through PTO. The aim of PTO surgery is to transfer the stress to the healthy lateral (external) meniscus compartment. This surgery eliminates the deformity by correcting the varus deformity and positioning the tibia toward the mechanical axis (1–7). Kurosawa and Doi (17) demonstrated that tibia vara is a primary determinant of joint compression forces at the knee. They took radiographic measurements of tibia vara and the femorotibial angle and found that a higher correlation existed between tibia vara and knee joint compression forces. In a study based on a finite elements model study, Cook et al. (18) concluded that increasing varus resulted in increasing compressive stress in the medial tibial physis, up to a level of seven times more than the normal level when the varus was in a position at 30°. Further, tensile stresses determined in the lateral tibial physis were increased above normal. In the current study, while there was approximately 3.95 MPa MES distribution on both the lateral and medial meniscus before PTO, the highest stress values were...
recorded as about 4.5 MPa in the lateral meniscus and 3.3 MPa in the medial part after PTO. Therefore, it was seen that the aim of transferring the stress to the healthy lateral side through surgery was achieved by the aid of PTO.

The relationship between tibia vara and calcaneal eversion is especially important for the function of the lower extremity. The degree of calcaneal eversion presents in standing and walking must at least be equal to the degree of tibia vara, so that the foot can prorate to allow the calcaneus to rest flat on the supporting surface (17–20). Limitations at the subtalar joint preventing sufficient calcaneal eversion can result in over-use syndromes – muscular imbalances; abnormal joint positions both proximally and distally at the hip, knee, midtarsal, and tarsometatarsal joints; and increased stresses on the surrounding soft tissues as the lower extremity compensates for these limitations (17). Due to changes in the calcaneal eversion angle and the position of the talocalcaneal, talonavicular and calcaneocuboid joints, stresses on the tarsal bones may be affected. With respect to loading on the tarsal bones; MES on all bones except for the navicula decreased in the PTO simulated model in the current study. These results clearly indicate that PTO can achieve decreased stresses on the tarsal bones in patients with tibia vara.

The load-bearing area of the ankle joint is a relatively small surface with thin cartilage. During walking, the load on the ankle joint can be calculated and is found to be approximately 3.9 times the body weight during the midstance phase of walking; that is to say, for a person weighing 75 kg, there is 2940 N on the talus. As the tibiotalar contact area is only a few cm² in size, each cm² bears a very high load. During running, this load increases multiple times. When the surface area changes in size, there will be an increase in load on the remaining cartilage. This happens after ankle fracture, when a lateral talar shift reduces the contact area, which will increase the average load/cm². In the case of an osteochondral defect the contact area also decreases, but probably not enough to cause damage to the healthy cartilage, as it also depends on alignment and peak stresses (19–21). In the current study, load bearing on the talus in the patient with tibia vara was incredibly high and might have a critical role in talar cartilage damage, and also MES on the talus was obtained in the subtalar articular surface (Figure 3). Thus, patients with varus malalignment may be candidates for subtalar arthritis.

Elastic conditions were used to define material properties of the articular cartilage, bones and the menisci. This assumption is valid for the short loading duration used in this investigation. In future investigations, proelastic conditions will be used to observe the time-dependent properties of the soft tissue. A shortfall in this study was that the pantalar joint biomechanics, ankle ligaments and the effect of fibula, as well as the calcaneal eversion angle on MES on the tarsal bones before and after operation, were not evaluated, although this will also be evaluated in future studies.

### Table 2. FEA results of maximum equivalent stresses on menisci, tibia and tarsal bones

<table>
<thead>
<tr>
<th>Structure</th>
<th>MES in varus (MPa)</th>
<th>MES after PTO (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial meniscus</td>
<td>3.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Lateral meniscus</td>
<td>3.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Tibia</td>
<td>16.3</td>
<td>21.8</td>
</tr>
<tr>
<td>Talus</td>
<td>56.9</td>
<td>23.2</td>
</tr>
<tr>
<td>Calcaneus</td>
<td>55.4</td>
<td>32.1</td>
</tr>
<tr>
<td>Navicula</td>
<td>18.9</td>
<td>25.9</td>
</tr>
<tr>
<td>Cuboid</td>
<td>18.3</td>
<td>13.1</td>
</tr>
<tr>
<td>Medial cuneiform</td>
<td>6.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Middle cuneiform</td>
<td>11.7</td>
<td>8.8</td>
</tr>
<tr>
<td>Lateral cuneiform</td>
<td>4.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Figure 2. Stress distributions on the tibia: (A) before PTO; (B) after PTO.

In conclusion, performing medial open-wedge valgus osteotomy (PTO) in patients with tibia vara may achieve a decrease in stresses on the foot bones and the medial compartment of the knee, and may transfer the MES to the tibia.

Conflict of interest

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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References