The effect of medial condylar bone loss of the knee on coronal plane stability—A cadaveric study

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Abstract

Introduction: The quantitative effects of medial bone loss of the knee on both leg alignment and coronal plane stability are poorly understood. Materials and methods: Utilizing computer navigation, 5 mm bone defects of the medial distal femur (MDF), medial posterior femoral condyle (MPF), and medial tibial plateau (MT) were simulated in 10 cadaveric limbs, and alignment of the knee at various degrees of flexion were analyzed when applying standardized varus and valgus loads. Results: The 5 mm MPF defect significantly increased varus laxity at 90° of flexion by 3.3° ± 1.2° (p = 0.019), a 5 mm MDF defect resulted in a 2.2° ± 1.7° (p = 0.037) and a 2.1° ± 1.3° (p = 0.023) increase in laxity at 0° and 30° of flexion, respectively, and a 5 mm MT defect increased varus laxity at all flexion angles by 4.0° to 7.0°, but was only statistically significant at 30° (p = 0.026). Discussion: This study confirms and quantifies the theories of flexion and extension gap balancing, and pseudolaxity of the medial collateral ligament in the varus knee, the results of which can be used in preoperative planning and intraoperative decision making for both total knee and unicompartmental arthroplasty.

Keywords: Arthroplasty Osteoarthritis Computer navigation Varus Coronal plane stability

1. Introduction

The complex physiology and kinematics of the knee have motivated a limited number of studies to attempt to quantify its native coronal plane stability, and the target values for joint-line opening with varus and valgus stress [14,15]. While in total knee arthroplasty (TKA), an established concept is to create rectangular flexion and extension gaps to promote stability, studies have demonstrated that the normal lateral tibiofemoral articulation is physiologically lax relative to the medial compartment [9,11–13,15]. Furthermore, when performing a TKA for a severe, varus deformity, over-resection of bone in the lateral compartment may be required to obtain appropriate mechanical alignment and implant placement, thus increasing lateral compartment instability [7]. The delicate balance between over-stabilizing a TKA and possibly limiting range of motion, versus allowing too much varus and valgus motion leading to instability and early clinical failure is difficult to achieve, and relies heavily on the surgeon’s preoperative understanding of knee kinematics, and each patient’s respective ligament laxity and deformity [4,5].

In varus knee osteoarthritis, patients often present with variable amounts of subchondral bone loss in the medial distal femur, posterior femoral condyle, and tibial plateau, which ultimately can lead to varus angulation and coronal plane instability. However, the quantitative effects of medial compartment bone loss on both leg alignment and coronal stability is poorly understood. Information to this regard would prove useful for 1) preoperative planning regarding the targeted amount of alignment correction to restore ligament balance, and 2) the amount of medial compartment bone loss that may be expected based on the preoperative deformity during both medial unicompartmental and total knee arthroplasty. Therefore, the aims of our study were to quantify the overall coronal laxity of the native, nonarthritic knee through flexion and extension, and to determine the effects of specific bone defects of the medial distal femoral condyle, medial posterior femoral condyle, and medial tibial plateau on varus and valgus laxity. Based on the principles of flexion and extension gap balancing, our hypothesis is that a medial tibial defect will result in a relative increase in varus angulation throughout flexion and extension, but a medial distal femoral condylar defect will only effect varus angulation in full extension, while a medial posterior femoral condylar defect will only effect varus alignment in ninety degrees of flexion.

2. Materials and methods

This was a cadaveric study utilizing computer navigation to assess the effect of medial condylar bone defects on both overall coronal and varus stability at 0°, 30°, 60°, and 90° of knee flexion. Ten fresh-frozen human cadaveric specimens of lower limbs (hip to toe) were used for this study. The age of the individuals at the time of death ranged from forty-one to sixty-seven years (mean, 56 years). Prior to formal testing of these specimens, a pilot study utilizing a single fresh-frozen
human cadaveric lower limb was performed to test the experimental protocol, which was approved by our institutional review board (IRB).

All specimens were thawed at room temperature for at least twenty-four hours prior to testing. Prior to inclusion in the protocol, specimens were excluded if they demonstrated evidence of previous surgical procedures or significant anterior-posterior or medial-lateral ligamentous instability on clinical examination. In addition, a specimen was excluded if it demonstrated significant medial, lateral, or patellofemoral arthritis after dissection. The subtrochanteric region of the femur was securely fixed to a vice attached to the operating table in a horizontal position to control rotation during stress testing, while the tibia was suspended off the end of the table. An anterior midline incision was made, followed by a standard medial parapatellar arthrotomy for visualization of the articular surface. Based on our pilot specimen, it was determined that the anterior horns of the medial and lateral menisci had to be released to accurately perform registration of the navigation system. The remaining intraarticular structures of the knee, including posterior horns of the medial and lateral menisci, anterior cruciate ligament, and posterior cruciate ligament were kept intact.

At this stage, all preparations were done to utilize the Praxim Nanostation knee navigation software for total knee arthroplasty (Praxim, La Tronche, France). Pin fixation was utilized for the distal femur and proximal tibia for placement of their respective arrays for anatomic registration and referencing. Bone morphing acquisitions of the femur and tibia were performed to obtain the mechanical axis of the limb, in addition to digitization of the transepicondylar axis as a primary femoral rotation reference, and the posterior condylar axis as a secondary femoral rotation reference [2, 10, 17]. Morphing of the distal femur and tibia reproduces a 3-dimensional computer replica of the anatomy that is accurate to within 1 mm and 1°. A stainless steel, threaded hook was inserted through the tibial crest 25 cm distal to the joint line, in an anterior to posterior direction [15].

The patella was reduced in the femoral trochlea prior to coronal plane stress testing. Using computer navigation, resting (neutral) alignment at 0°, 30°, 60°, and 90° of flexion of each native cadaveric specimen (after exposure but prior to creation of a bony defect) was determined by placing the limb in a continuous passive motion (CPM) machine under axial load, with the femoral head completely reduced in a sawbones pelvis that was pinned to a wooden board on the operating table. Stress testing was then performed in the native knee, at 0°, 30°, 60°, and 90° of flexion. During varus/valgus stress testing, a standardized force of 9.8 Nm (4 kg applied 25 cm distal to the knee joint) was applied utilizing a spring gauge scale attached to a cable tie inserted in the hook [15]. The flexion angle and mechanical varus/valgus angles between the tibia and femur were measured in real-time utilizing the navigation software (Fig. 1). For each respective flexion angle being tested, the varus and valgus stress measurements were performed three times, and the values for each measurement were averaged. For standardization, varus angles were presented as negative values (in degrees), while valgus angles are presented as positive values (in degrees).

Next, sequential defects were made in the medial proximal tibia (MT), medial distal femoral condyle (MDF), and medial posterior femoral condyle (MPF), resecting 5 mm of bone with each defect. Resection levels were standardized using an adjustable, navigated cutting block on the tibia (Nanoblock®, Praxim), which allows navigated, fine adjustment of the varus/valgus angle, height, and slope of the tibial cut. Tibial defects were made 90° to the mechanical axis in the coronal plane, and in 3° of posterior slope in the sagittal plane. Distal femoral and posterior femoral condyle defects were created utilizing a robotic saw-guide positioner (iBlock®, Praxim), which automatically positions the bone cutting block as planned to a maximum cut depth of 5 mm (Figs. 2 and 3). Prior to varus/valgus stress testing, resection accuracy of both the tibial and femoral defects were verified to be within 1 mm and 1° utilizing the navigation system cut controller (planar probe) placed on the cut surface, and by measuring the thickness of the resected portions with a handheld caliper. After each individual defect was created, resting alignment and varus/valgus stressed alignments were respectively recorded in 0°, 30°, 60°, and 90° of flexion for that defect. The sequence in which the defects were created was altered so that each of the three defects was tested first on at least three separate specimens, thus allowing the measurement of each individual defect independently, as well as all three defects combined. The increase in varus or valgus alignment was calculated as the difference between the angle recorded for that defect and the native knee at the same degree of flexion.

3. Statistical methods

A repeated measures ANOVA analysis was performed to analyze if a difference was present in the mean mechanical varus and valgus alignment angles during stress testing at 0°, 30°, 60°, and 90° of flexion, both between the native knee and each individual defect, and between the native knee and all defects combined. P-values of <0.05 were considered significant. All analyses were performed using SPSS software (SPSS Inc., Chicago, Illinois).

4. Results

All results are presented using a femoral coordinate system based off of the femoral mechanical axis and the transepicondylar axis. Table 1 summarizes the resting (neutral) coronal plane alignments of all specimens throughout flexion, and the results following varus and valgus stress testing of the native cadaveric knee. The overall coronal laxity of the knee increased as the knee was brought into greater flexion, ranging from 2.2° ± 1.5° (mean ± SD) at 0° of flexion, to 10.8° ± 4.2° at 90° of flexion. At 0° of flexion, the difference in the coronal plane alignment angle when applying both a varus and valgus stress compared to the neutral values was not significant, while at 90° of flexion, the mean difference in the alignment angle with varus and valgus load was 7.1° ± 1.0° and 3.7° ± 0.9° (p < 0.001), respectively, when compared to the neutral values obtained during continuous passive motion.

None of the medial compartment defects resulted in a statistically significant difference in coronal plane alignment angles with valgus stress testing at any flexion angle (maximum change 1.3°), while all three medial defects (MT, MDF, MPF) resulted
in an increase in varus laxity from baseline under varus stress testing. However, the flexion angle at which the increased laxity reached statistical significance varied for each respective defect (Fig. 4). The 5 mm medial posterior femoral condyle defect increased varus laxity at 90° of flexion by $-3.3° \pm 1.2°$ ($p=0.019$), but did not change significantly from 0° to 60°. In contrast, a 5 mm medial distal femoral condyle defect resulted in an increase in varus laxity by $-2.2° \pm 1.7°$ ($p=0.037$) and $-2.1° \pm 1.3°$ ($p=0.023$) at 0° and 30° of flexion, respectively, but did not reach significance at 60° and 90° of flexion. The 5 mm medial tibial defect increased varus laxity at all flexion angles by $-4.0° \pm 1.5°$ to $-7.0° \pm 4.4°$, but only reached statistical significance at 30° of flexion ($p=0.026$), with an increase of $-4.8° \pm 1.9°$. The combined effect of all three defects being present significantly increased varus laxity at all flexion angles by $-4.0° \pm 2.4°$ to $-7.7° \pm 2.8°$ ($p<0.001$ for all flexion angles).

5. Discussion

In the setting of medial compartment osteoarthritis and varus malalignment, patients often present with variable amounts of attritional bone loss. While medial compartment bone loss is expected to increase varus instability, the quantitative effects of these defects have not yet been quantified. The aims of this study were to quantify the effects of specific condylar bone defects of the medial compartment on varus laxity at 0°, 30°, 60°, and 90° of flexion. The 5 mm MPF defect significantly increased varus laxity at 90° of flexion by $3.3° \pm 1.2°$ ($p=0.019$), a 5 mm MDF defect resulted in a $2.2° \pm 1.7°$ ($p=0.037$) and a $2.1° \pm 1.3°$ ($p=0.023$) increase in laxity at 0° and 30° of flexion, respectively, and a 5 mm MT defect increased varus laxity at all flexion angles by 4.0° to 7.0°, but was only statistically significant at 30° ($p=0.026$). Prior to this study, these values had not yet been defined, and they may prove useful both in preoperative planning and intraoperative decision making for both total knee and unicompartmental arthroplasty.

With regards to varus and valgus stress testing in the native, nonarthritic, cadaveric knee, we found that with increasing knee flexion, the overall coronal laxity increased. In this study, the overall coronal varus and valgus laxity was $2.2° \pm 1.5°$ at 0° of flexion, increasing to $7.0° \pm 2.4°$ at 30° of flexion, and $10.8° \pm 4.2°$ at 90° of flexion. In contrast, Casino et al. reported the results of knee coronal laxity utilizing navigation software in twenty patients with osteoarthritis and either varus or neutral alignment, and found the overall varus–valgus laxity to be $7.7° \pm 1.4°$ at 0° of flexion. The difference in overall laxity seen at 0° of...
flexion between the two studies may be explained by the presence of medial compartment arthritic changes in their specimens, in addition to the lack of standardization of the maximum load they applied when applying a varus or valgus stress [3].

In addition to demonstrating an overall increase in coronal plane laxity, with increasing knee flexion, we found a significant increase in laxity with application of a varus stress versus a valgus stress, indicating that the lateral structures of the knee are physiologically more lax. At 90° of knee flexion, under a standardized varus stress, the varus alignment significantly increased by 7.1° ± 1.0°, while the valgus alignment under valgus load increased 3.7° ± 0.9° (p < 0.001) from the resting alignment. These results are consistent with those reported by Van Damme et al., who in a cadaveric study utilized a fluoroscopy based surgical navigation system to demonstrate medial-lateral joint-line opening on valgus stress to be 2.6 mm at 0°, 5.1 mm at 30°, and 7.1 mm at 90° of flexion, while the average lateral joint-line opening on varus stress was 3.1 mm at 0°, 5.9 mm at 30°, and 8.1 mm at 90° of flexion [15]. Similarly, Tokuhara et al., in an MRI based study of twenty normal knees, demonstrated that at 90° of flexion, the lateral joint gap opened by 6.7 ± 1.9 mm with a varus stress, whereas the medial joint gap opened by only a mean of 2.1 ± 1.1 mm, also consistent with the lateral structures of the knee having increased laxity [14]. Thus, our results are consistent with previous reports that the flexion gap in normal knees may not be rectangular, raising the question of whether obtaining a mediolaterally balanced total knee replacement should be the intraoperative goal with total knee arthroplasty [11–13].

As expected, bone loss in the distal femur significantly altered coronal stability in 0° and 30° of flexion, whereas posterior femoral condyle defects significantly altered coronal plane stability in 90° of flexion. In addition, tibial defects affected coronal stability from 0° to 90° of flexion, although our results were only statistically significant at 30° of flexion, likely due to the limited number of specimens tested. These results are not surprising, as they follow the surgical concepts of balancing the flexion and extension gaps in total knee arthroplasty [8,9,16]. However, the specific quantitative values presented in this study may prove useful with both preoperative planning regarding the targeted amount of alignment correction to restore ligament balance, and the amount of medial compartment bone loss that may be expected based on the preoperative deformity.

The native, resting alignment in this study, in 0° of flexion, was −0.3° ± 2.3°. However, with the creation of a 5 mm distal femoral bone defect, the mechanical alignment significantly increased by 2.2° ± 1.7° with application of a varus stress at 0° of flexion. In addition, an isolated, 5 mm medial tibial defect increased the mechanical alignment by 4.0° ± 1.5° under a varus stress at 0° of flexion. The stress applied to these cadaveric specimens may correlate with the physiologic, varus, weightbearing loads seen by the knee in a patient with medial compartment, attritional bone loss. Therefore, based on the degree of distal femoral or medial tibial bone loss appreciated intraoperatively, the degree of correction required to return to neutral mechanical alignment can be extrapolated. This information may be especially applicable when performing a medial, unicompartmental knee arthroplasty, as in a total knee arthroplasty, coronal plane balancing can be performed via procedures in both the medial and lateral compartments, but with a medial, unicompartmental knee arthroplasty, restoration of appropriate mechanical alignment can only be achieved via work on the medial compartment of the knee. Pseudolaxity of the medial collateral ligament (MCL) in a patient with medial compartment osteoarthritis and varus alignment is a commonly appreciated finding, and it is paramount that the surgeon assess whether there is a fixed or flexible varus deformity preoperatively. In the setting of a flexible deformity, quite often there is pseudolaxity of the MCL, indicating that the native tension can be restored with correction of the mechanical alignment. Therefore, the quantitative values presented in this study may both prove useful for surgeons as a reference to the degree of correction required to restore the native tension of the MCL, and the amount of medial, attritional bone loss present based on the preoperative deformity. The importance of appropriate postoperative mechanical alignment has been noted in multiple studies, as over-correction in valgus of the preoperative deformity leads to early degeneration of the lateral compartment, while under-correction of the deformity leads to increased polyethylene wear and recurrent varus alignment [1,6].

Therefore, this cadaveric study provides the knee surgeon with values for knee laxity in 0°, 30°, 60°, and 90° of flexion utilizing a computer navigation system, in addition to the quantitative effects of 5 mm osteochondral defects of the medial tibial plateau, distal femoral condyle, and posterior femoral condyle on varus alignment. While additional in vivo work is necessary to study the in vitro results obtained from this study, this study confirms and quantifies the theories of flexion and extension gap balancing and pseudolaxity of the medial collateral ligament in the varus knee, the results of which can be used in preoperative planning and intraoperative decision making for both total knee and unicompartmental arthroplasty.

Conflict of interest

The authors have no conflicts of interest to disclose that are directly related to this study.

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References
