The Analysis of Strain Distribution on Corrected Varus Knee under Walking Load Condition

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Abstract. The knee is one of the important joint of human body to carry the body load. The deformities of knee joint affect the human activities. To treat the deformity knee, close-wedge High Tibial Osteotomy (HTO) was one of the popular techniques to adjust the strain distribution on the deformity knee close to the normal by shifting the mechanical axis toward the lateral side. This research aims to evaluate the strain distribution on the varus knee corrected by zero degree, three degree valgus and three degrees varus close-wedge HTO under walking load. The result was shown the lowest strain distribution occur on the three degrees varus model following by zero degree and three degree valgus model respectively. The surgeon should be correct the varus knee by three degrees varus close-wedge HTO to get the strain distribution on the bone closet to the normal knee.

1. Introduction
Knee is one of the important joint to carry the body weight and activities load of human life. The mechanical axis of normal knee joint is an axis to transfer load from the body to foot is determined by drawing a vertical line from the center of femoral head to the middle of femoral epicondyle and passes through the ankle joint [1]. The center of varus knee was shifted to the lateral side of mechanical axis and the hip-knee-ankle (HKA) was negative as shown in figure 1 but it becomes zero in case of neutral alignment [2].

![Figure 1. Load bearing axis and Mechanical axis of varus knee[3](image)](image-url)
The correction of mechanical axis in varus knee at proximal tibia with a high tibial osteotomy (HTO) to adjust the strain distribution on the deformity knee close to normal had a good long-term result [4, 5, 6, 7]. From previous study, the varus knee corrected by close wedge HTO had a lower strain distribution than varus knee but higher than varus knee inserted total knee prosthesis under daily activities [8] but the angle of correction affect the strain distribution on the bone model [9]. This research aims to evaluate the strain distribution on the lower extremity after corrected the varus knee by close wedge HTO with zero degree, three degrees valgus and three degrees varus of mechanical axis by finite element analysis to find the suitable angle of correction for support the surgeon’s decision in surgical process.

2. Material and methods

2.1. Three-dimensional model

2.1.1. Varus knee model3D model of varus knee was scanned by computerized tomographic (CT) scanner and was reconstructed by ITK-SNAP program as shown in figure 2.

![Figure 2.3D model of varus knee.](image)

2.1.2. Tibial condylar plate and fixation screwsTo stabilize the bone after corrected by close wedge HTO technique, the tibial condylar plate was used to fix the cut proximal tibia. 3D tibial plate was constructed from CT data same as the bone and the screw fixation was created by SolidWorks software. The plate and screw was shown in figure 3.

![Figure 3.3D models of tibial condylar plate and screw fixations.](image)

2.1.3. Ligament and meniscus modelThe knee joint was consisted of four ligaments as anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL) and lateral collateral ligament (LCL) to stabilize the joint and meniscus to absorb the load transferred. The meniscus and ligaments were created based on actual anatomy position by SolidWorks software as shown in figure 4.
2.2. Virtual simulation

This research used the virtual simulation method to remove the partial of proximal tibia, correct the mechanical axis and insert the tibial plate and screw fixations to fix the tibia fragment. The varus knee model was corrected with three angles as zero degree, three degrees valgus and three degrees varus by varying the degree of cutting proximal tibia. 3D models of corrected varus knee by close-wedge HTO were shown in Figure 5.

![Figure 4](image_url) 3D models of four ligaments and meniscus.

Figure 5. 3D models of corrected varus knee by close-wedge HTO: (a) Zero degree, (b) Three degrees valgus and (c) Three degrees varus.

2.3. Material properties

Material properties of cortical bone, cancellous bone, four ligaments, meniscus, screw fixation and tibial condylar plate were assumed homogeneous, isotropic and linear elastic [10, 11, 12]. The elastic modulus and Poisson’s ratio of all material was shown in Table 1.

| Materials                  | Elastic modulus (MPa) | Poisson’s ratio |
|----------------------------|-----------------------|-----------------|
| Cortical bone              | 14,000                | 0.30            |
| Cancellous bone            | 600                   | 0.20            |
| ACL, PCL and LCL           | 345                   | 0.40            |
| MCL                        | 332.2                 | 0.40            |
| Meniscus                   | 12                    | 0.45            |
| Stainless steel            | 200,000               | 0.30            |

2.4. Loading and boundary condition

The position of muscular forces for walking load for daily activities was act on the proximal femur. The body weight act on the top of femur and the model was fixed at the end of distal tibia as shown in
figure 6. The magnitude of muscular force and body weight was separated in x-, y- and z-axis under walking condition were shown in table 2.

![Diagram of muscular forces and body weight on proximal femur](image)

**Figure 6.** The position of muscular forces and body weight act on the proximal femur.

| Position            | Force          | Fx(N) | Fy(N) | Fz(N) |
|---------------------|----------------|-------|-------|-------|
| 1 Fix displacement  | 0.0            | 0.0   | 0.0   |
| 2 Body weight       | 0.0            | 0.0   | -836.0|
| 3 Hip contact       | 54.0           | 32.0  | -229.2|
| 4 Intersegmental resultant | 18.8     | 12.8  | 78.2  |
| 5 Abductor          | 58.0           | 4.3   | 86.5  |
| 6 Tensor fascia latae, proximal part | 7.2   | 11.6  | 13.2  |
| 7 Tensor fascia latae, distal part | -0.5  | -0.7  | -19.0 |
| 8 Vastus lateralis  | -0.9           | 18.5  | -92.9 |

**Table 2** The muscular force act on proximal femur under walking condition [14].

2.5. Finite element model
Four-node tetrahedral element was used in this study to create the mesh model as shown in figure 7 to analyze the equivalent of total stain distribution on bone model and von Mises stress distribution on tibial condylar plate and screw fixation. The femur model had a total of 10,463 nodes and 54,110 elements. The tibia model had a total of 28,092 nodes and 270,748 elements. The fixations had a total of 6,013 nodes and 25,512 elements.

![3D mesh models](image)

**Figure 7.** 3D mesh model: (a) Femoral bone, (b) Tibia bone and (c) Plate and screw fixation.
3. Result and discussion
All results was analysed by finite element analysis to evaluate the equivalent of total strain distribution on the varus knee corrected by close wedge HTO with three different degree as zero degree, three degrees valgus and three degrees varus under walking condition. The maximum equivalent of total strain on three models was shown in table 3 and the strain distribution on femur and tibia were shown in figure 8 and 9 respectively.

| Model                | The maximum equivalent of total strain (µε) |
|----------------------|--------------------------------------------|
| Zero degree          | 3,595.86                                   |
| Three degrees valgus | 3,644.01                                   |
| Three degrees varus  | 3,545.41                                   |

The maximum equivalent of total strain on the varus corrected by close wedge HTO with zero degree had 3,595.86 microstrain and three degrees varus had less than by 1.40% and three valgus had greater than by 1.34%. The maximum equivalent of total strain of all models did not exceed 25,000 microstrain that safe for the bone damage after correct the varus knee [15, 16]. The surgeon should be correct varus knee by close wedge HTO with three degrees varus for the lowest maximum equivalent of total strain.

**Figure 8.** The equivalent of total strain distribution on femur under walking condition: (a) Zero degree, (b) Three degrees valgus and (c) Three degrees varus.

**Figure 9.** The equivalent of total strain distribution on tibia under walking condition: (a) Zero degree, (b) Three degrees valgus and (c) Three degrees varus.
The maximum von Miss stress on tibial condylar plate and nine screw fixations for three different models was shown in table 5 and the stress distribution on tibial condylar plate and set of screw fixation were shown in figure 10 and 11 respectively.

**Table 4** The maximum von Miss stress on tibia condylar plate and nine screw fixations.

| Model                | Tibial condylar plate | Screw 1 (MPa) | Screw 2 (MPa) | Screw 3 (MPa) | Screw 4 (MPa) | Screw 5 (MPa) | Screw 6 (MPa) | Screw 7 (MPa) | Screw 8 (MPa) | Screw 9 (MPa) |
|----------------------|-----------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Zero degree          | 421.49                | 20.96          | 50.00          | 106.00         | 66.35          | 15.24          | 16.87          | 17.65          | 27.16          | 195.44         |
| Three degrees valgus | 118.37                | 25.34          | 73.84          | 117.94         | 45.56          | 28.53          | 17.90          | 38.30          | 93.40          | 18.69          |
| Three degrees varus  | 129.61                | 23.98          | 25.48          | 103.97         | 81.98          | 14.38          | 14.38          | 22.67          | 25.07          | 105.55         |

**Figure 10.** The von Mises stress distribution on tibial condylar plate under walking condition: (a) Zero degree, (b) Three degrees varus and (c) Three degrees valgus.

**Figure 11.** The maximum von Mises stress on the screw fixation under walking condition (Mpa) on model three degree valgus.

The highest maximum von Mises stress occurred on tibial condylar plate of zero degree model which was used to fix the top of proximal tibia. The maximum von Mises stress of all plate and screw models did not reach the yield strength of stainless steel (750 MPa) [17] that safe for implant failure.

**4. Conclusion**
The prediction of strain distributed on lower extremity by finite element analysis was a popular tool for surgeon to plan the surgical treatment. The current investigation could lead to the acquisition of useful knowledge in order to establish of efficacious method to prevent the bone fracture after corrected the knee by close-wedge HTO[18]. The angle of correction did not affect the strain distribution on the bone model that showed less difference of maximum equivalent of total strain on
three model lower extremities. The surgeon should be correct the varus knee by three degreesvarus close-wedge HTO to get the strain distribution on the bone closet to the normal knee.

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