Exploration of different boundary conditions in the sideways falling situation in hip fracture finite element modeling

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Summary. This study investigated the influence of different boundary condition settings on one sideways falling condition, an incident which often causes hip fracture in older adults. Three MRI-based FE models of a single person were created in the sideways falling condition. Results of this study showed that the presence of a fixed support at the distal end of the femoral shaft can reduce the highest stress at the fracture prone region of the femoral neck. It was also found that the location of the impact force applied can substantially alter the stress distribution pattern within the femoral neck.

Key words: finite element modeling, hip fracture, sideways falling, boundary condition

Introduction

Hip fracture is a major public health problem leading to high morbidity, mortality, and disability in older adult population. The global annual hip fracture number was estimated to 1.6 million in 2000 [7] and 7000 hip fractures were reported in Finland in 2010 [9]. Hip fractures are not only debilitating events, but also lead to substantial financial burden for societies worldwide. Its
financial burden is estimated to reach $131.5 billion by 2050 [6]. Over 90% of the hip fractures are caused by falls [5] (Figure 1).

During the two last decades, finite element (FE) method has been exploited in the hip fracture studies in order to understand the mechanism of the hip fracture. Interest has been especially in simulations where falling conditions are studied. However, literature reveals that different boundary conditions (BC) have been used in simulating even the same falling situation in terms of the fall direction. This variance in the BCs might have affected the results of FE models between studies. Recent experimental study by Choi et al. [1] addressed this issue and suggested that the BCs at the distal end of the proximal femur can influence the result. However, to the best of our knowledge, little is still known how different BCs affect the result. Therefore, the aim of this study is to elaborate this issue by creating magnetic resonance image (MRI)-based FE models of one person in one sideways falling situation with three different BCs. Specific attention was laid on following differences in the BCs; 1) presence or absence of the restrain BC such as a fixed support at the distal end of the femoral shaft, and 2) location of the impact force applied (on femoral head or on greater trochanter) (Figure 1). Mayhew et al. [10] found that the superoposterior region of the femoral neck is the hip fracture prone region due to the thin cortical bone layer. Thus, it was especially focused to study how different BC settings affect the stresses at this fracture prone region.

**Materials and Methods**

MR image data of proximal femur region was obtained from one adult female participant in our previous study [11]. The study protocol was approved by the Ethics Committee of the Pirkanmaa Hospital District, and a written informed consent was obtained from the participant before measurements.

The MR images were first manually segmented by delineating the periosteal and endocortical boundaries of the cortical bone using a touch panel (Wacom Tablet Clintiq 12WX, Wacom Technology Corp., Vancouver, WA.) with a medical image processing software the ITK-SNAP[16] (www.itksnap.org). The segmented bone geometry was then smoothed in MeshLab (Visual Computing Lab – ISTI – CNR, http://meshlab.sourceforge.net/) using smoothing method described by Taubin.[14] This method was chosen to avoid shrinkage of the geometry inherent in the smoothing. The smoothed proximal femur geometry consisted of cortical bone and trabecular bone, the latter denoting the inside volume of the endocortical bone layer. Thus, although the trabecular bone actually forms porous structure, the trabecular bone geometry was modeled as the non-porous homogeneous material. The smoothed proximal femur geometry was imported into SolidWorks (SolidWorks Corp., Waltham, MA.) for the 3D solid body generation.

The 3D solid body geometry of the proximal femur was imported into ANSYS 15.0 (ANSYS Inc., Houston, PA.) for the FE meshing and model analysis. A 10-noded tetrahedral finite element was used to mesh the cortical and trabecular geometries of the proximal femur. Average element edge size was set for 2mm for the entire geometry. A model consisted of approximately 190000 elements and 300000 nodes. The cortical and trabecular bone of proximal femur were modeled as homogeneous isotropic, linear elastic materials. The Young’s modulus of 17GPa[4,8,13] and 1500MPa[4,13] were set for the cortical and trabecular bone, respectively. Poisson’s ratio was assumed as 0.33[4,8,13] for both bone types. To simulate the sideways falling, the most commonly used force direction was chosen from the experimental studies conducted by Pinilla et al.[12] and Courtney et al.[2,3] The femoral shaft was tilted at 10° with respect to the ground and the femoral neck was internally rotated by 15°[2,3,12] (Figure1). A simulated impact force of magnitude of 5000N was applied.
In total, three FE models (A, B, and C) were created in order to address two research questions; 1) the effect of the presence or absence of the restrain BC at the distal end of the femoral shaft on the femoral neck stress distribution, and 2) the corresponding effect of location of the impact force applied (on femoral head or on greater trochanter). Figure 1 shows difference in the BCs in three FE models. Similar to the previous study conducted by Verhulp et al.[15], the impact force was equally distributed to the surface nodes of the femoral head (model A and B) /greater trochanter (model C) within 5mm layer perpendicular to the force. Also, surface nodes of the lateral side of the femoral head (model C) /greater trochanter (model A and B) in 5mm layer perpendicular to the force were restrained only in the direction of the force. For the model B, the face of the distal end was fully restrained (fixed support). The von Mises stresses were calculated from the FE models and stress distribution on the proximal femur in anterior and posterior views were plotted in order to analyze the result qualitatively.

Figure 1. Sideways falling, force direction, and different BC descriptions in three models. (1) The sideways falling condition. (2) The force direction in coronal view, the BCs for model A, B, and C for the location of the impact force applied and restraining BCs. (3) The force direction in sagittal view and BC at the distal end of femoral shaft represented by red line which represents the face where fixed support was applied in model B. Yellow areas in the picture 2 and 3 represent the surface nodes where the BCs were applied.
Results

Stress distributions of the three models were plotted in Figure 2. By comparing the model A with the model B, the highest stresses at superoposterior region of the distal femoral neck site get decreased from 144 MPa in the model A to 110 MPa in the model B. Otherwise, the stress distributions between models A and B seemed to be quite similar. On the other hand, by comparing the model A with the model C, stress distribution pattern changed substantially. The highest 144 MPa stress at superoposterior region observed in the model A was reduced considerably down to 65 MPa in the model C. Furthermore, relatively low stress at inferoanterior region of the proximal femoral neck site in the model A (about 30 MPa) was increased drastically to about 120 MPa in the model C.

Figure 2. Stress distributions in the proximal femurs in the sideways falling condition in three models A, B, and C. Top three models are stress distributions in posterior view and are slightly rotated superiorly in order to see stress distribution at superoposterior region of the femoral neck more clearly. Lower three are stress distributions in anterior view and were also slightly rotated inferiorly in order to compare the high stress values at inferoanterior region of the proximal femoral neck site from model C with other two models’ values. Vertical coloured bar on the left represents the von Mises stress magnitude.
Discussion

In this study, three proximal femur FE models of a same person were created in order to investigate how different BCs in the same sideways falling situation modify the stress distribution, especially at hip fracture prone region such as superoposterior region of the femoral neck. Results from the models A and B showed that presence of the fixed support (in model B) can reduce the highest stress at the superoposterior region. This was mostly likely attributed to decrease in bending of the femoral neck due to the fixed support at the distal end of the femoral shaft. On the other hand, the results from the models A and C showed changing the location of the impact force applied can alter the stress distribution pattern more remarkably if the distal end was not fixed. High stress region seems to shift from superoposterior region of the distal femoral neck site to inferoanterior region of the proximal femoral neck site if the impact force was applied on the greater trochanter instead of femoral head.

Boundary conditions at the distal end of the femoral shaft reflect the position of the knee at the impact from the fall. According to Choi et al. [1], absence of the restrain BCs at the distal end represents that the knee is in the air at the impact while its presence represents that the knee is in contact with ground. In the majority of the previous proximal femur FE modeling studies, the restrain BCs were applied at the distal end of the femoral shaft. In those studies, the mechanical testing was also performed for the validation of the FE models, and the distal end of the femoral shaft needed to be restrained to perform the test successfully. Thus, restrain BC was applied at the distal end to match with the mechanical test setting. The presence of the restrain BC seems to have an effect to reduce the highest stress at this fracture-prone region. This implies that the knee position in the fall may be another factor contributing to the fracture.

The impact force was commonly applied on the femoral head in the most of previous proximal femur FE studies. This was also due to the mechanical test setting. However, in the real falling situation, undoubtedly lateral side of the greater trochanter experiences the impact force. Indeed, the present study showed that stress distribution pattern changed drastically if the impact force was applied on the greater trochanter. This result questions the validity of using the femoral head as the location of the impact force applied. The result also insists that other regions in addition to the superoposterior region may have high fracture risk in a real falling situation.

In conclusion, the present FE modeling study demonstrated that difference in BCs in a same sideways falling situation can alter the stress distribution patterns. Therefore, in the future hip fracture FE modeling studies, it is necessary to give a rationale for why specific BCs were chosen and what the meaning of chosen BCs is in terms of life falling situation.

References


