

Quantitative Analysis of the Weakening Effect of Cortical Windows in Non-Osteoporotic and Osteoporotic Proximal Femurs

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ABSTRACT

Introduction: Cortical windows in the proximal femur are used in musculoskeletal tumor surgery for both biopsy and curettage purposes. This study aimed to evaluate the effect of cortical windows on the weakening of the proximal femur under axial and rotational loading using finite element analysis and determine the safe widths, levels, and axial positions.

Methods: The proximal femurs of a healthy 37-year-old male and an osteoporotic 76-year-old female were 3D modeled using computed tomography scans. A total of 192 different models were created with 225 mm-long oblong windows with widths of 10, 12.5, 15, and 17.5 mm at 8 different levels and 3 different axial locations. Each model was tested for axial and rotational loading up to failure point.

Results: The safe maximum width for all levels and both bones was found to be 10 mm ($p < 0.001$). Anterolateral and posterolateral placement of cortical windows did not offer biomechanical advantages under axial loading ($p > 0.05$).

Conclusion: The study quantitatively shows that keeping the width of the cortical window below 15 mm and proximal to the lesser trochanter is an important factor in keeping the fracture risk low during biopsy procedures. Additionally, anterolateral or posterolateral placement of cortical windows does not offer any biomechanical advantages. The findings of this study can help clinicians to avoid iatrogenic fractures during biopsy and curettage procedures.

Keywords: Femur, finite element analysis, biomechanics, bone biopsy

Introduction

The proximal femur is a common location for bone lesions. In younger patients, most lesions are due to primary bone tumors such as unicameral bone cysts or aneurysmal bone cysts (1); whereas in older patients, most lesions in the proximal femur are metastatic lesions (2). Curettage is used in primary lesions such as unicameral bone cysts (3). In elderly patients, open bone biopsy may be employed in cases of unknown primary origin or for local augmentation purposes (2).

Curettage and open bone biopsies are performed through windows in the cortical bone. In the proximal femur lateral (4) or posterolateral approaches (5) are recommended as the optimal biopsy route. This leaves a defect in the cortex, which may create an area of difference in the elastic modulus and as such a stress-riser effect (6). Consequently, a complication of this procedure is fracture at the biopsy site (5). Clark et al. (7) established in cadaver femora that oblong holes with rounded ends afford the greatest residual strength, and increasing the width

causes a significant reduction in strength. There have also been reports of subtrochanteric fractures after femoral neck fracture fixation with screws if the screws cluster around the lesser trochanter (8). There is no widely accepted cut-off value in the literature for the safe maximum width of the window, whether it makes any difference to do it posterior or anterolaterally, as well as the relative weakening effect of the level of window in the failure load.

This study systematically analyzes the effect of different widths, levels and axial locations for the cortical windows effect on non-osteoporotic (NOP) and osteoporotic (OP) proximal femur using quantitative computed tomography (CT) based FE modeling.

Methods

The Istanbul Physical Therapy and Rehabilitation Training and Research Hospital Ethics Committee approvals were obtained for the study (IRB: 2024-04). Informed consent was obtained from the patients for anonymous use their imaging and demographic data.



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CT Data and FE Modeling

Proximal femur CT scans of a healthy 37-year-old male (Slice thickness: 1.0 mm) and an OP 76-year-old female (Slice thickness: 1.0 mm) who presented with a pelvic fragility fracture on the ipsilateral side were used for this study. The bone was modeled using triangular shell elements with a thickness of 0.4 mm and a size of 3 mm for the outer surface of the cortical bone, and tetrahedral solid elements with a size of 3 mm were used for the rest of the bone. There were approximately 27,000 triangular plates and 180,000 tetrahedral elements in both models. The elastic modulus and strength of each element were calculated by converting Hounsfield units into Young’s modulus and yield strength according to Keyak et al. (9). Figure 1 shows the difference in bone quality between the two femurs.

Loading and Constraint Conditions

For both models, the femoral shaft was cut perpendicular to the mechanical axis about 12 cm from the lesser trochanter for the biomechanical setup. The distal one third was restrained (Figure 2a). Axial loading was simulated with a force vector applied to the joint surface along the mechanical axis of the femur, which was set to be 6° from the anatomic axis (Figure 2b). Rotational loading was simulated with a force vector directed posterior to anterior acting on the femoral head (Figure 2c). The loading area and direction of the force on the femoral head were consistent between all cases.

Generation of the Bone Window Model

Eight window levels were defined for both models. The uppermost window had its proximal border approximately 10 mm from the tip of the greater trochanter. The window moved exactly 10 mm distally in each level. A description of the levels in terms of their proximal and distal ends is summarized in Table 1. All windows had a uniform height of 225 mm. Four different widths of 10, 12.5, 15, and 17.5 mm were used. Axially, the windows were cut either anterolaterally, posterolaterally, or at the midline (Figure 3). Figure 4 shows a midline cortical window of

12.5 mm width at level 4. For the two models, a total of 192 cortical windows were created.

Simulation

Each of the 192 models with cortical windows was tested for axial and rotational loading, resulting in a total of 384 analyses. In each case, the applied load started at 25 N and then increased to 25 N at each step until there was a failure of more than five surface elements. The load to failure in the NOP femur without a cortical window was 4525 N for axial loading and 950 N for rotational loading. The load to failure in the OP femur without a cortical window was 2350 N for axial loading and 925 N for rotational loading. Failure under axial load occurred in the neck in both cases, whereas failure under rotational load occurred just above the lower constraint in the shaft.

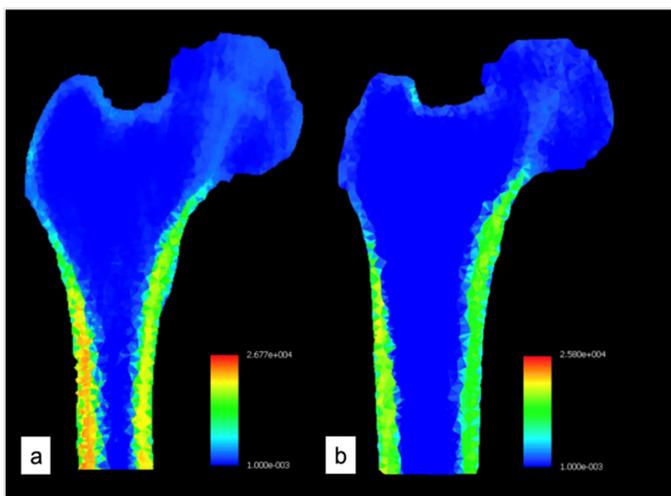


Figure 1. Coronal sections of (a) non-osteoporotic (NOP) and (b) osteoporotic (OP) femurs. Note the high Young’s modulus at the lateral cortex of NOP as well as the prominent primary compressive trabeculae compared to OP femur

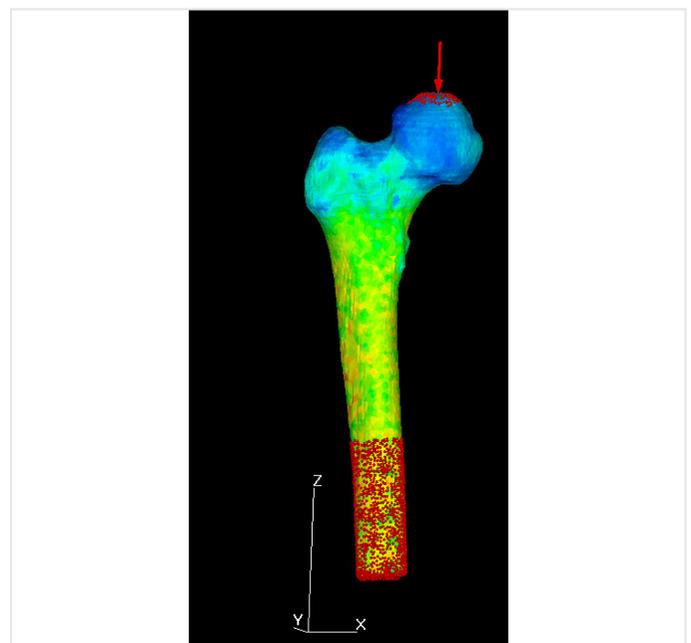


Figure 2. The load direction, area and the distal constraint are shown

Table 1. Description of the proximal and distal ends of the cortical windows

Level	Description
1	Starts approximately 1 cm below the tip of GT at the level of the superior femoral neck, ends above LT
2	Starts approximately at the level of mid-femoral neck, ends above LT
3	Starts approximately at the level of the inferior femoral neck, ends above LT
4	Starts below the GT, ends at the upper half of LT
5	Starts at the proximal end of the LT, ends at the lower end of the LT
6	Starts at the midpoint of LT and ends below LT
7	Starts at the inferior half of the LT, ends below the LT
8	Starts below LT and ends below LT

GT: Greater trochanter, LT: Lesser trochanter

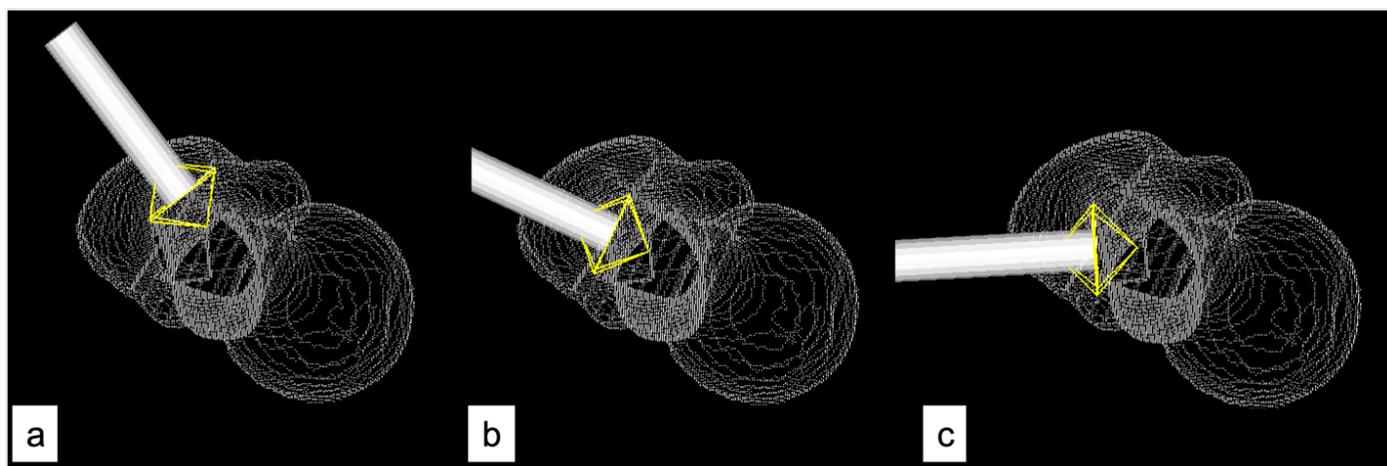


Figure 3. Axial position of the posterolateral (a), midline (b), and anterolateral (c) windows

Statistical Analysis

The load to fracture in both models was reported using descriptive statistics. Python and SPSS (Chicago, IL) were used for statistical analysis and graphical representation. A $p < 0.05$ was accepted as significant. One-Way ANOVA test was used to compare the failure loads between anterolateral, midline and posterolateral windows for each width for both axial and rotational loading. Linear regression was used to study the correlation between the level of the window and the fracture load. The chi-square test was used to establish the significance of increased risk of fracture through the cortical window.

Results

Non-Osteoporotic Bone Model

The One-Way ANOVA test used to compare the fracture loads for anterolateral, midline and posterolateral windows showed that for all cases in the NOP model, there was no difference in making the window posterolateral, at the midline or anterolaterally in terms of average load to failure in both axial ($p > 0.05$) and rotational loading ($p > 0.05$).

For axial loading, no reduction in fracture load or fracture through the cortical window was observed with a 10 mm wide cortical window. Five cases of iatrogenic fractures were observed with a 12.5 mm window, seven cases with a 15 mm window and eight cases with a 17 mm window. No iatrogenic fracture or decrease in fracture load occurred at or above level 4. Figure 5 shows the scatter plots of the fracture loads for each window width except for 10 mm with regression lines. For windows below level 4, linear regression suggests that on average, an additional decrease of 6.5% in the fracture load is expected for each level below the 12.5 mm window ($r^2 = 0.48$, $\beta = -292.5$, $p = 0.004$), an additional decrease of 7.5% is expected for the 15 mm window ($r^2 = 0.40$, $\beta = -340.0$, $p = 0.01$), and an additional decrease of 11% is expected for the 17.5 mm window ($r^2 = 0.80$, $\beta = -497.5$, $p < 0.0001$).

19/20 iatrogenic fractures (95%) occurred in windows at level six or lower and at and above 12.5 mm width. There was a significant association between fracture status and location [$\chi^2 = 13.39$, $p < 0.05$, odds ratio (OR): 330]. Fractures were more likely to occur inside these parameters (63%) than outside (4%), when compared to the expected values.

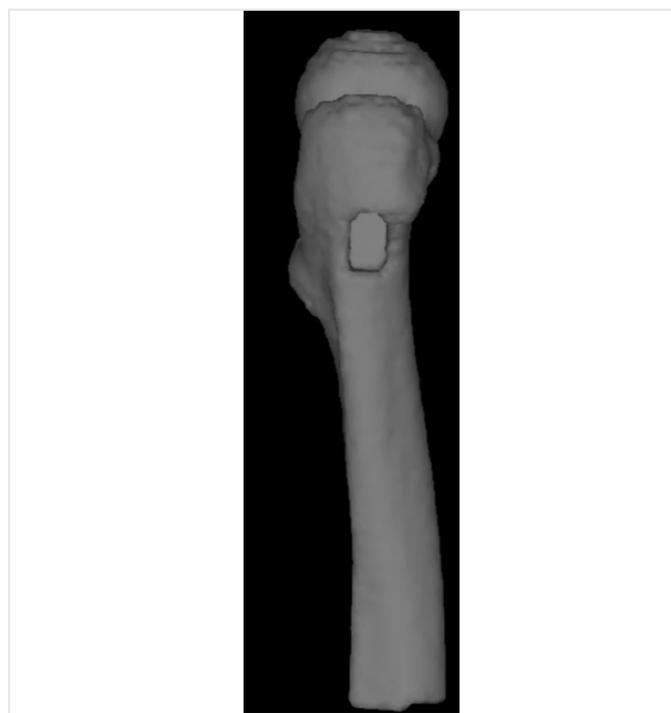


Figure 4. Example of a midline 12.5 mm-wide cortical window

For rotational loading, no reduction in fracture load or iatrogenic fracture was observed with a 10 mm wide cortical window. Two cases of iatrogenic fractures occurred with a 12.5 mm window, one with a 15 mm window and three with a 17.5 mm window. All iatrogenic fractures, except the 17.5 mm window at level 8, failed under a similar load as the native bone.

Osteoporotic bone model

The One-Way ANOVA test used to compare the fracture loads for anterolateral, midline, and posterolateral windows showed that for most cases in the OP model, there were no differences observed except for the posterolateral window in the 12.5 mm ($p = 0.02$) and 15 mm ($p = 0.004$) widths and for anterolateral, midline, and posterolateral windows for the 17.5 mm width ($p < 0.001$) where a significant decrease in rotational failure load was observed.

For axial loading, no reduction in fracture load or iatrogenic fracture was observed with a 10 mm wide cortical window. One case of iatrogenic fractures were observed with 12.5 mm window, 8 cases with 15 mm window and 9 cases with 17 mm window. No iatrogenic fracture or decrease in fracture load occurred at or above level 3. Figure 6 shows the scatter plots of the fracture loads for each window width of 15 and 17.5 mm with regression lines. For windows below level 3, linear regression suggests that on average an additional decrease of 2.9% in the fracture load is expected for each level below with 15 mm window ($r^2=0.23$, $\beta=-66.5$, $p<0.05$) and an additional decrease of 7.7% is expected for 17.5 mm window ($r^2=0.39$, $\beta=-177.1$, $p<0.01$).

For rotational loading, no reduction in fracture load or iatrogenic fracture was observed with a 10 mm wide cortical window. Four cases

of iatrogenic fractures occurred with a 12.5 mm window, 10 with a 15 mm window, and 11 with a 17.5 mm window. There was a significant reduction in fracture loads when the window was made posterolateral (Figure 6). The posterolateral cortical window resulted in an additional 8.8% decrease in rotational fracture load with each level ($r^2=0.74$, $\beta=-79.5$, $p<0.0001$).

17 of 18 fractures (94%) occurred at level four or lower and at or above 15 mm width. There was a significant association between fracture status and location ($\chi^2= 5.68$, $p<0.05$, OR: 1235). Fractures were more likely to occur inside these parameters (63%) than outside (2%) compared to the expected values.

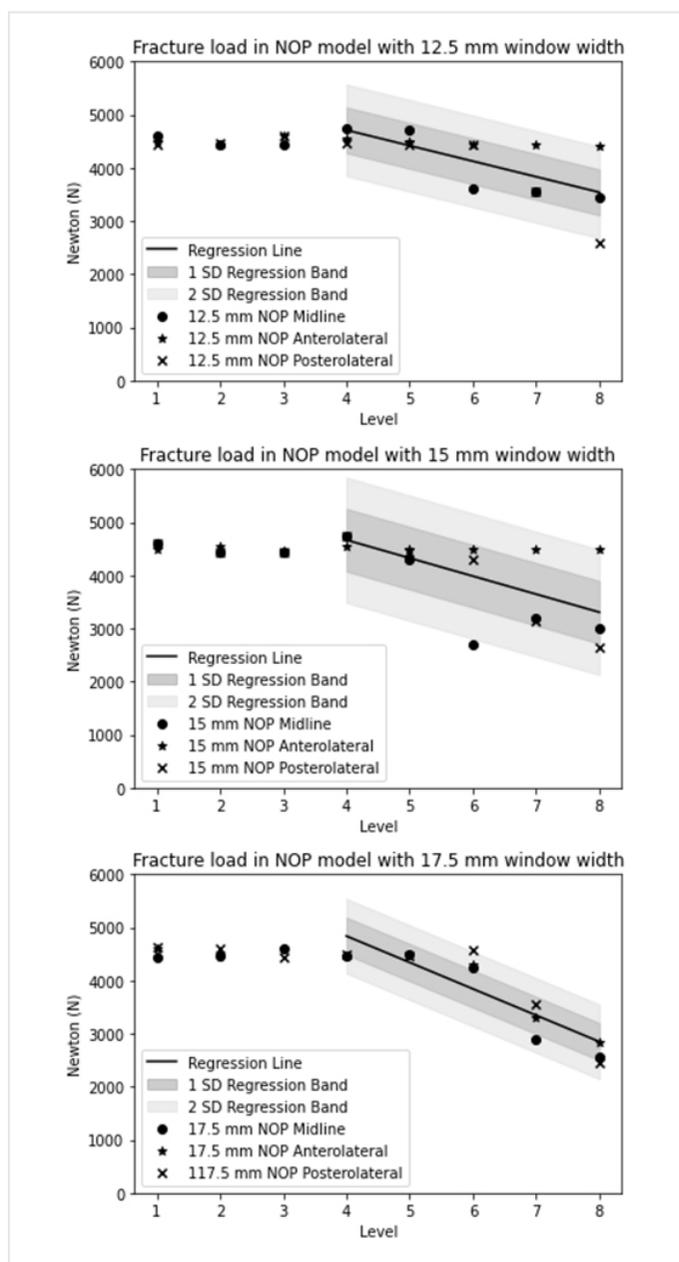


Figure 5. Fracture loads in the non-osteoporotic bone model under axial loading for 12.5, 15, and 17.5 mm wide windows

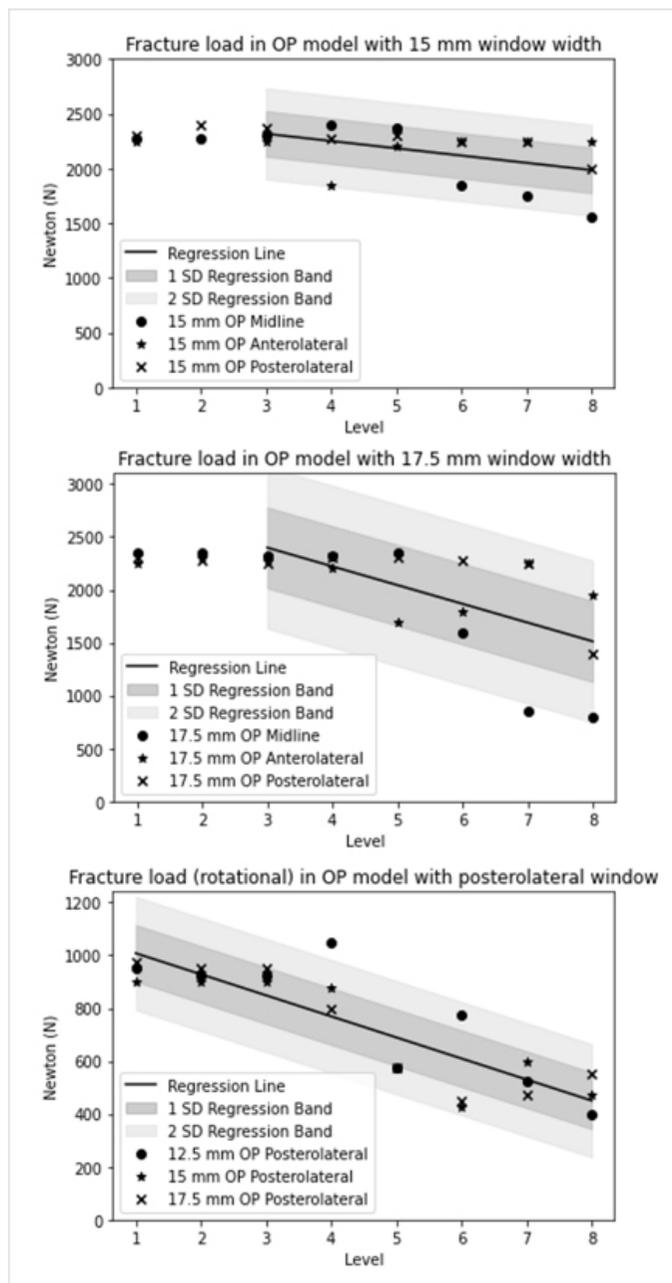


Figure 6. Fracture loads in the osteoporotic bone model under axial loading for 15 and 17.5 mm Windows and fracture load under rotational loading for 12.5, 15, and 17.5 mm posterolateral windows

All cases of fractures under axial loading in the NOP femur occurred at higher loads than in the native OP bone.

Discussion

There are three main options for studying the effects of these factors on iatrogenic fracture risk after bone biopsy. Observation studies, while frequently performed, do not allow for the control of every variable. Another option would be cadaver studies, which are expensive and hard to obtain in many institutions. In contrast to these options, one of the main advantages of FEA is the ability to change variables in a controlled simulation to perform numerous analyses and detailed investigations.

In a similar study, Hayashi et al. (10) found 15 mm to be the critical width for bone biopsy. In contrast to their study that used younger patients, we compared the OP and NOP femurs and still concluded that 15 mm is a critical value for fracture risk. In addition, our results indicate that 12.5 mm cortical windows are almost as safe as 10 mm windows. Although there were fractures in Levels 7 and 8 in the NOP group but not in the OP group, this was because the NOP patient had a much higher failure load than the OP patient and the older femur failed through the neck before it was put under sufficient stress for the 12.5 mm window to be a problem.

A novel part of this study is looking at the effects of anterolateral, midline, and posterolateral windows, which might also have value beyond tumor and trauma surgery. Anterolateral cortical windows, for example, are used for component removal in revision arthroplasty, and the effects of cortical windows at different axial positions and levels can provide insight in such situations (11-13). The hypothesis behind the anterolateral and posterolateral windows was the possibility of safely enlarging the windows as the window is moved away from the lateral cortex, which has the largest tension forces. This was not the case. The posterior to anterior force at the femoral head with a fixed shaft was tested to simulate the rotational moment at the proximal femur. Failure under rotational loading was not as sensitive to the size and level of the cortical windows as failure under axial loading, except for the posterolaterally placed windows. Under axial loading, 10 mm and 12.5 mm windows did not decrease load to failure, and failure still occurred through the neck in the OP bone. There is a moderate to high correlation of the window level with a decrease in fracture loads in larger window widths. It does not provide meaningful protection for the axial loading in both models, and in the OP bone, it significantly decreases the rotational strength of the femur.

The results also indicate a moderate to high correlation of the window level with the decrease in fracture loads in larger window widths. These are significant because of the large forces acting on the hip joint. Bergmann et al. (14) reported that average load at hip joint is 238% of body weight when walking at 4 km/h, and 260% of body weight when going downstairs. More significantly, in another study from the same lead author, the peak forces at the hip during stumbling were reported to be twice those during other activities, which in some cases corresponded to more than eight times the body weight (15). Thus, small decreases in fracture loads might correspond to fractures with low-energy trauma.

The decrease in failure load for axial loading in our study was similar to the results reported by Hayashi et al. (10). They have reported up to a 32% percent decrease in fracture load between biopsy levels 2 and 3 for 15 mm wide windows, and up to a 51% percent decrease between biopsy levels 2 and 3 for 20 mm wide windows, within one standard deviation. Note that although iatrogenic fractures in the NOP bone occurred in 12.5 wide windows, these were still under higher loads than those applied to the OP bone.

An improvement over this model would be to include the tension effect of the hip abductors. Tsai et al. (16) reported that the abductor force at the greater trochanter can be as high as 71.4% of the joint contact force. The abductors contribute to the tension forces at the lateral cortex and possibly increase the occurrence of fractures and decrease the strength with windows below their attachment site. Another improvement would be to study the effect of cyclical loading. This would ideally require the use of cadaver femora. Hsu et al. (17), in their study investigating subtrochanteric fractures after multiple screw fixation of femoral head, demonstrated that it might take up to 120,000 cycles for failure.

Study Limitations

There are a few limitations to this study. We included only one sample for OP and NOP femurs. One of the main advantages of FEA is the ability to draw meaningful conclusions with small sample sizes because of the ability to test the same model under different conditions. Saláček et al. (18), for instance, used a single pelvis CT model to study fixation biomechanics in sacral fractures. However, a larger sample size as well as more patients from both sexes would allow us to detect smaller differences as well as draw conclusions for each gender.

Conclusion

Cortical windows for biopsy or curettage may significantly weaken the bone. There seems to be no biomechanical advantage in making the window anterolateral or posterolateral instead of midline. Our results show that if large windows need to be made, keeping the width of the cortical window below 15 mm and the lower end higher than the midpoint of the LT is an important factor in keeping the fracture risk low in both OP and NOP bone.

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Informed Consent: Informed consent was obtained from the patients for anonymous use their imaging and demographic data.

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