AN INVESTIGATION OF THE FEMORAL NECK SUSCEPTIBILITY TO FRACTURE INCORPORATING THE EFFECTS OF AGE-REMODELLING AND STRESS REDUCTION

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SUMMARY

Age-related bone remodeling causes fragility of the femoral neck, increasing fracture risk in elderly populations. We investigated the effects of age-remodeling and stress-reduction on femoral neck regions using the Finite Strip Method (FSM), verifying the possibility that the femoral neck is likely to undergo fracture through two mechanisms: yielding and local buckling. We hypothesized that femoral necks of young subjects are more prone to fracture by yielding, whereas those of elderly subjects are more susceptible to local buckling. Slices from CT-scans of 8 subjects corresponding to lowest area moment of inertia were segregated into cortex and trabeculae. Geometric properties for each strip were obtained from the CT-scans. The FSM was implemented on models comprising both cortex and trabeculae that incorporated the effects of age-related bone remodeling, and reduction in physiological stress on bone (due to weight loss). Comparisons were made with FS analyses performed on only the cortex, in order to ascertain the contributions of the trabeculae to femoral neck strength. Femoral neck models of simulated young subjects manifested a predisposition to yielding, whereas femoral neck models of simulated elderly subjects were prone to buckling. Trabecular degradation and cortical thinning during aging render the femoral neck susceptible to buckling failure.

INTRODUCTION

The frequency of hip fractures is greater in elderly populations than in younger ones. This trend may be due to a combination of trabecular bone loss, cortical thinning, and increased outer cortical diameter. During a sideways fall, the femoral neck region is likely to fail through two different mechanisms: local elastic buckling or yielding. Local elastic buckling occurs when a portion of the cortex abruptly bulges inwards or outwards as a result of an increase in the compressive force exerted by the ground during impact. On the other hand, yielding occurs when the bone material disintegrates at a microscopic level, initiating a crack that develops into a full fracture. It is likely that local elastic buckling is prevented by the presence of dense trabecular networks that provide lateral support to the cortical shell. This implies that elderly people would suffer a greater risk of fracture by buckling, owing to gradual degradation of their trabecular networks. This also suggests that the femoral neck of young populations is more likely to fail only by yielding, and not local buckling. It is to be noted that failure by local elastic buckling will reduce the strength that is predicted by pure yielding. The failure behavior and the details of age-related changes that lead to bone fragility over the course of the human lifetime are yet to be specified.

METHODS

3D models of the femoral neck were generated using Mimics software (Materialise Inc, Ann Arbor, MI, USA) from the intact femora of seven human cadavers (4 female, 3 male, ages 52-68). Consequently, the narrowest cross-section of the femoral neck was chosen for buckling analysis. The cortical shell and trabecular core were modeled using the donut and butterfly mesh schemes of VA-BATTS software (www.simtk.org), respectively. Voronoi tessellation was performed on the trabecular structure using nucleation points generated by the butterfly mesh available in the VA-BATTS software, in order to generate finite strip models.

The Finite Strip Method was then implemented using the CUFSM software (www.ce.jhu.edu/bschafer/cufsm/) on the two models: cortex alone, and cortex with trabeculae. Winter’s equations were then applied on the buckling load values obtained to establish whether the bone ultimately failed by elastic buckling or yielding. Finally, bone remodelling with age was simulated for young, middle-aged, and the elderly, and similar analysis performed. The contribution of the trabeculae to the total bone strength was determined for all the models.

RESULTS AND DISCUSSION

The results showed that the trabecular core contributed between 18% and 49% to the strength of the femoral neck in the fall mode. The local buckling shapes for models at various ages and different load adaptations were considerably different. It was observed that the elastic local buckling strength of cortical shells decreased with an increase in age for all subjects. Although similar in trend, it was observed that the elastic buckling strengths of the integrated models were higher than those of the respective cortical shell models. In contrast to the cortical shell models, the integrated cortical shell-trabecular core models appeared to have a greater amount of
change in the elastic buckling strength with respect to age. The buckling strength contribution of the trabecular core was found to decrease with an increase in age for all subjects. However, for all the subjects, the contribution of the trabecular core to the total predicted strength was seen to increase with age. It was also noted that the predicted strength of all the elderly models of various subjects reduced with a decrease in the percentage load adaptation. The CPU run time for each of the simulations of the integrated cortical-trabecular models was less than 6 hours, as compared to less than 15 seconds for each cortical shell model.

FSM analysis helped discern inter-subject differences in the trabecular contribution to the predicted strength of the femur. Local buckling strength depends considerably on the mean thickness of the thinnest segment of the cortical shell, which is usually located between the superior and posterior regions of the section. Hence, local buckling was found to be initiated between superior and posterior regions for each individual submodel. Just prior to the onset of buckling, the trabecular core reinforces the cortical shell by providing lateral support. The contribution of trabecular core to the overall strength of the femoral neck was calculated as the difference between the strength of the integrated cross-section (i.e., containing both cortex and trabeculae) and the strength of the cortical cross-section.

CONCLUSIONS

In conclusion, this study shows that there is indeed an increased likelihood of the occurrence of buckling fractures in the femoral neck regions of elderly subjects, owing to gradual degradation of the trabecular networks. It also shows that the femoral neck regions of relatively young subjects are more likely to succumb to yielding fracture prior to the onset of buckling fracture, owing to their dense trabecular networks.

Figure 1. Segmentation of the femoral neck CT-image into cortical and trabecular bones using VA-BATTS meshing tool. A: Anterior; I: Inferior; S: Superior; P: Posterior

Figure 2: Buckling images for the finite strip models at three ages, showing variations in post-buckling shape (A: 20s; B: 50s; C: 80s; D: 80s – 10%; E: 80s – 20%).

Figure 3: Graph showing the trends in the normalized strength (Fn/Fy) with slenderness ratio, for the cortical bone only, and the integrated model with both cortical and trabecular bone.

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