OFF-AXIS LOADS CAUSE FAILURE OF THE DISTAL RADIUS AT LOWER MAGNITUDES THAN AXIAL LOADS: A FINITE ELEMENT ANALYSIS

Karen L. Troy[1] and Mark D. Grabiner[1]
[1]University Illinois at Chicago, Chicago, IL USA
E-mail: klreed@uic.edu

INTRODUCTION

Distal radius fractures are among the most common fall-related injuries in older women. Numerous studies have quantified upper extremity fall biomechanics with the goal of identifying possible interventions to reduce the peak force on the wrists, thereby reducing the number of fractures [1-3]. Fracture initiation depends both on the force applied to the bone and upon the strength of the bone itself; thus, poor bone quality has been implicated as a factor in distal radius fractures. Generally, an intervention to improve bone quality (such as anti-resorptive therapy) is considered successful if bone mineral density (BMD) can be increased by 2-4% [4].

Cadaver and finite element studies have previously quantified the force required to cause a distal radius fracture [5]. To date, however, only simple axial loads on the radius have been considered. Because most falls onto the hands result in off-axis loads, we considered the possibility that a combination of loading modes would significantly influence the fracture strength of the distal radius. Here, we used a validated finite element model of the distal radius, scaphoid, and lunate, to explore the effects of loading direction and changes in BMD on predicted fracture strength.

METHODS

The right wrist of a 53 year old female volunteer was imaged with computed tomography. Geometrical and density data for the radius, scaphoid, and lunate were extracted using custom-written software (Matlab 7.01) and a finite element model was built using ANSYS 10.0. Bone material properties were assigned to each element based on the average Hounsfield value (HU) for those voxels located in the vicinity of the element using the following equations [6-8]:

Cortical: $\rho = 1.09 + 0.000445 * HU$
$E = 2065 * \rho^{3.09}$
Cancellous: $\rho = 0.0012 * HU + 0.17$
$E = 1904 * \rho^{1.64}$

A cut-off value of 672 HU was assigned to distinguish cortical (HU>672) from cancellous (HU<672) bone. A 2.5 mm-thick layer of cartilage was created on the distal articular surface of the radius. The ligaments that directly attach the radius, scaphoid, and lunate were included in the model as non-linear springs (Figure 1).

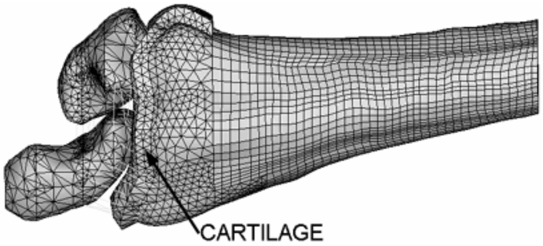

Figure 1 Dorsal view of the FE mesh

A total of 26 models were run in which bone density and loading direction were varied. In each model a ramped 3000 N load was applied to the radius via the centroids of the scaphoid (1800 N) and lunate (1200 N). Series 1 consisted of all models to which an axial load was applied. BMD was changed from its baseline value in either the cancellous bone only, the cortical bone only, or all bone of the radius, by -4%, -2%, +2%, or +4%. Combined with a model in which no change of BMD was simulated, this resulted in 13 total simulations. Series 2 was identical to Series 1 except that the loading direction was changed to simulate a worst-case off-axis load, described by a unit vector [-0.1385 -0.3562 -0.9241] in the [lateral, volar, axial] directions [9]. (A negative axial load indicates the force is directed from the wrist towards the elbow).

For each simulation, each element's first and third principal stress (s_1 and s_3) were recorded during the ramped load, and element failure was determined using the Mohr-Coulomb criterion of:

$$s_1/\sigma_{ty} - s_3/\sigma_{cy} \geq 1 \qquad [10]$$

where σ_{ty} and σ_{cy} are the material's tensile and compressive yield stresses, respectively. Once element failure was determined for a given load, a custom written algorithm (Matlab 7.01) determined the total volume of contiguous failed elements. A crack large enough to propagate was assumed to have developed after a total volume of 350mm^3 failed [11].

RESULTS AND DISCUSSION

Loading direction had a strong influence on predicted fracture strength. For the unchanged (baseline) BMD model, an axial load caused fracture at 2752 N. In contrast, the off-axis load applied to the same unchanged BMD model predicted fracture at 1448N (Figure 2).

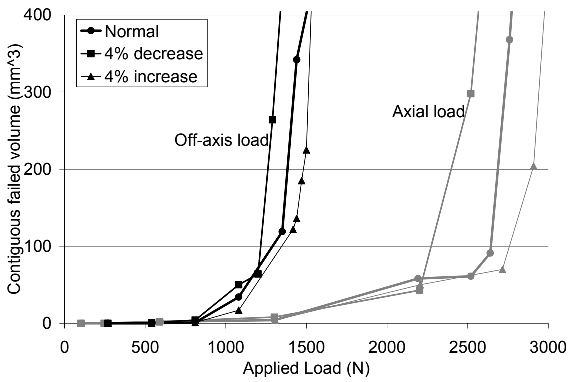

Figure 2 Load versus failed contiguous volume for on- and off-axis simulations. BMD changes for all bone (cortical and cancellous) are shown. Fracture was assumed at 350 mm^3, however fracture load appears to be somewhat insensitive to the specific volume cut-off.

Changes in BMD caused small but nonlinear changes in predicted fracture strength. Increasing or decreasing cortical bone density did not make a large difference in fracture strength compared to changes in either cancellous or all bone (Figure 3).

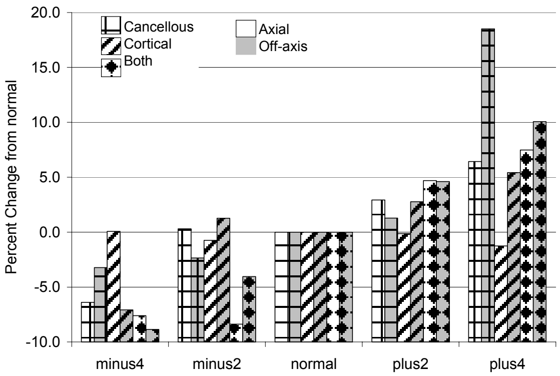

Figure 3 Percent change in fracture strength compared to the normal BMD values after changes in cancellous, cortical, or all bone.

SUMMARY/CONCLUSIONS

Loading direction had a strong effect on predicted fracture strength. In contrast, systematic changes in bone mineral density had a much smaller affect on fracture strength. It is possible that changes in BMD in more structurally important locations, such as those that may be initiated through functional loading or through local application of bone growth factors, may cause more substantial enhancements in bone strength. Just as it is possible for people to minimize peak ground impact forces on the hands during a fall, it may be possible to voluntarily influence the direction of ground impact on the wrist.

REFERENCES

[1] DeGoede, K.M. and J.A. Ashton-Miller, J Biomech, 2002. 35 p. 843-8. **[2]** Chou, P.H., et al., Clin Biomech , 2001. 16 p. 888-94. **[3]** Chiu, J. and S.N. Robinovitch, J Biomech, 1998. 31 p. 1169-76. **[4]** Liberman UA et al. N Engl J Med 1995.333 p 1437-1443 **[5]** Pistoia, W., et al., Bone, 2002. 30 p. 842-8. **[6]** Lotz, J.C. et al., J Comput Assist Tomogr, 1990. 14 p. 107-14. **[7]** Wirtz, D.C., et al.J Biomech, 2000. 33 p. 1325-30. **[8]** Snyder, S.M. and E. Schneider J Orthop Res, 1991. 9 p. 422-31. **[9]** Troy, KL and MD Grabiner. *ISB Proc.* 2005. Cleveland, OH **[10]** Keyak JHet al. J Biomech 1998.31 p125-133 **[11]** Keyak JH and Rossi SA. J Biomech 2000.33 p209-214

ACKNOWLEDGEMENTS

Funding source: F32 AG25619-02 (KLT)