Journal of Orthopaedic Research
6:32–38, Raven Press, Ltd., New York

Strain Rate and Mineral Content in Fracture Models of Bone

J. D. Currey

Department of Biology, University of York, York, England

Summary: I reanalysed data from my previous work to determine the extent to which a model for the loading-rate dependence of the fracture of cortical bone, put forward by Carter and Caler, fits this independently derived data set. In particular, the extent to which the generality of the model is vitiated by its ignoring the effect of mineralisation on strength was tested. The model was rather strongly corroborated. In addition, the reanalysed data show that yield strain is strongly strain-rate dependent, but that Young's modulus is rather unvarying over physiological strain rates. The implications of this for hypotheses concerning fracture of bone are discussed. **Key Words:** Bone—Mechanical properties—Loading rate—Mineralization—Modeling.

Many variables can affect the fracture properties of bone. Some, such as porosity and mineral content, are intrinsic to the material; others, such as strain rate or complexity of loading, are extrinsic. In recent years, Carter and co-workers (2–6) produced a series of articles on the fatigue properties of bone that examined in some detail the extrinsic and intrinsic factors affecting bone fatigue strength.

Recently, Carter and Caler (3) produced a "cumulative damage model" for the fracture of bone. This model is of considerable interest because it attempts to subsume the effects of both cyclical loading (fatigue) and the time over which loading occurs (creep) in a single model for failure. Carter and Caler concluded that:

> [T]he tension damage in bone reported by Carter and Hayes (1977) from high-stress, low cycle repeated loadings may actually be creep damage rather than fatigue damage as originally thought.

In brief, the reason for this may be that in high-stress cyclical loading the factor causing most of the damage to the bone material is the *time* spent at rather high tension stresses, rather than the reversals of loading.

The model of Carter and Caler makes predictions about monotonic tensile fractures. It predicts that bone will accumulate damage over time when stressed, even at low stresses, and that the bone will fracture when a certain amount of damage has accumulated. A low strain rate will allow more time for damage to accumulate at any particular stress than would be available at high strain rates. Therefore, low strain rates should result in lower tensile strength. The parameters of the model were derived empirically from creep data in Carter and Caler (2), and the model predicted that in human bone damage accumulated at a *rate* proportional to the instantaneous stress raised to the power 17.95. If the model is valid, human bone would have a strength of

$$\sigma_{ult} = 87\,\dot{\sigma}^{0.053},$$

where σ_{ult} is the ultimate tensile strength, measured in megapascals, and $\dot{\sigma}$ is the stress rate, in megapascals per second. Because their specimens had a rather uniform Young's modulus of elasticity,

Address correspondence and reprint requests to Dr. J. D. Currey at Department of Biology, University of York, York Y01 5DD, England.

Carter and Caler thought it reasonable to convert a stress rate directly to a strain rate, giving:

$$\sigma_{ult} = 147\dot{\epsilon}^{0.055}$$

where $\dot{\epsilon}$ is the strain rate in reciprocal seconds.

Carter and Caler showed that data produced for bovine bone (7,13) and for human bone (1) fit their model reasonably well, but did not discuss the data produced by Currey (9), perhaps because the analysis in that article was not done in a way helpful for their purposes. The data in that article can be reanalysed, however, to answer a number of questions. (Hereafter, I call these reanalysed data the "present data.")

1. Do the present data in general support the model for monotonic tensile loading?
2. The model of Carter and Caler applies to the *ultimate* tensile strength of bone. For many purposes the *yield* stress is of equal, or even of more interest. Does the model hold when applied to the yield stress?
3. The relationship between the stress rate (on which the model is based) and the strain rate was not measured by Carter and Caler, but was calculated assuming a particular value for Young's modulus (17 GPa). This was a reasonable procedure because their specimens varied little in Young's modulus, except for the small amount produced by differences in strain rate. The present data have specimens showing considerable variation in Young's modulus. To what extent does this vitiate a simple movement from stress rate to strain rate?
4. Because the compact bone used by Carter and Caler was rather uniform in its Young's modulus, it was probably also rather uniform in its mineral content. The present data include bone specimens of widely different mineral content. To what extent does ignoring or including these differences vitiate the model?
5. The present data include information on Young's modulus and yield strain. These two properties were not measured by Carter and Caler (3). What further information, if any, about the cause of fracture can be obtained by knowledge of these variables?

This article addresses these questions. The model of Carter and Caler seems reasonably robust over the range of strain rates included in the present data.

MATERIALS AND METHODS

The materials and methods used were reported fully in Currey (9). In brief, 35 specimens of bovine femora were tested in tension, wet, at room temperature, rather than at 37°C, as used by Carter and Caler, at various strain rates, from 10^{-4} s^{-1} to 1.6 $\times$ 10^{-1} s^{-1}. Stress rate was calculated as: (strain rate $\times$ Young's modulus). This range of strain rates is less than that investigated by Carter and Caler, who had the same lower bound but carried out tests up to 5 $\times$ 10^2 s^{-1}. Therefore, the findings reported here relate only to the lower half of the log range of strain rates reported by Carter and Caler. The greatest strain rates in the present data are probably not much less, however, than the rate of loading in clinical situations leading to fracture.

I have not found information on the strain rate that bone is likely to be subjected to when undergoing an ordinary fracture, as opposed to a fracture imposed by high-velocity missiles, but show evidence here on which to base an educated guess. Rubin and Lanyon (12), in investigating the strain imposed on bones of the horse and dog during fast locomotion, found that the maximum strain was about one-third the yield strain. The strain rate, as the foot impacted the ground, was 0.1 s^{-1}. A fracture could probably occur in the same time as the achievement of maximum strain during fast locomotion. This implies a strain rate of 0.3 s^{-1}. Similarly, Preuschoft (11) estimated from force plate data the time over which the stress rises very rapidly in the lower extremities in jumps onto a hard surface. The evidence here is less direct but implies a strain rate for dangerous loading of, at the outside, 1 s^{-1}.

The mechanical properties determined were Young's modulus of elasticity, yield stress, yield strain, and ultimate tensile stress. The mineral content of the dry specimens was determined by comparing the mass before and after ashing.

The range of ash contents was from 60.35 to 67.85% ash per mass of dry bone. Although this range may not seem large, it produces large differences in mechanical properties (8).

The statistical analysis reported by Currey (9), though valid, is not helpful for present purposes. Carter and Caler produce equations of the type $Y = kX^b$. This was done by converting the raw data to logarithms, performing a linear regression analysis on the transformed data, and then reconverting the linear equation to a power law equation. Here, I do the same. The regression analysis is performed in the logarithmic domain, in which the regression is of the standard additive form:

$$Y = a + bX_1 + cX_2$$

When converted back into the arithmetic domain, the regressions produce a model of the form:

$$Y = a(X_1^b \times X_2^c)$$

where Y is some mechanical property of the bone material, X_1 is the amount of mineralization, and X_2 is the loading rate.

RESULTS

The equations in the Appendix give the results for four dependent variables: ultimate tensile strength, (the variable discussed by Carter and Caler), yield stress, yield strain, and Young's modulus of elasticity. Yield stress is never greater than ultimate tensile strength and, in these specimens, never very much less. Therefore, the equations relating ultimate tensile strength and yield stress to the independent variables might be expected to be similar. Young's modulus and yield strain were not reported by Carter and Caler (3), but I include them here for completeness and because some interesting consequences flow from their examination. The equations in which the effects of two independent variables are considered simultaneously come from the use of forward stepwise regression.

Ultimate Tensile Strength

Equation A1 shows that a considerable proportion of the variation in ultimate tensile strength (58%) is explained by variation in mineral content. Equations A2 and A3 show that stress rate and strain rate explain almost the same amount of the variation as does mineral content. As might be expected, strain rate and stress rate are highly correlated ($r = 0.99$); thus, it is reasonable for many purposes to consider them together. (Hereafter, "loading rate" refers to both stress and strain rate indifferently.) Loading rate was chosen with no direct knowledge of the mineral content of the specimen. Insofar as I could guess, from a knowledge of the anatomy of the bone, I tried to produce a variety of loading rates over the various mineral contents. It is not surprising, therefore that neither stress rate nor strain rate significantly correlated with mineral content ($r = 0.20$ and 0.13, respectively). Loading rate and mineral content were independent. Equations A2 and A3 can be compared directly with those of Carter and Caler.

$$\sigma_{ult} = 192 \times \dot{\epsilon}^{0.090} \text{ (present data)}$$
$$\sigma_{ult} = 147 \times \dot{\epsilon}^{0.055} \text{ (Carter and Caler).}$$

$$\sigma_{ult} = 78 \times \dot{\sigma}^{0.091} \text{ (present data)}$$
$$\sigma_{ult} = 87 \times \dot{\sigma}^{0.053} \text{ (Carter and Caler).}$$

These equations are reasonably similar, although the exponents in the Carter and Caler equations are obviously lower. The specimens used by Currey (9) were deliberately chosen, however, from a knowledge of the histology of the bone, to give a fairly wide range of mineral contents; therefore, mineral content is likely to be an important explanatory variable. The specimens of Carter and Caler were probably more uniform. Using a forward stepwise regression on the present data, one can separate out the effects of mineral and of loading rate, as is shown in equations A4 and A5. Clearly, this procedure has greatly improved the agreement between the exponents in the two independently derived sets of equations.

Yield Stress

Carter and Caler were concerned with ultimate strength. Surely, however, it is the stress at which the bone *yields* that is determined by their model, at least that part of it concerned with monotonic tensile fractures.

Ordinary compact bone loaded in tension shows a fairly sharp yield point. Before this point, the stress-strain trace usually shows only slight curvature, if any. After the yield point, the curve flattens considerably, and there is usually little extra stress before the specimen fractures, although there may be considerable extra strain. Sometimes, however, the bone is brittle, and there is no postyield deformation. This occurred in 2 of my 35 specimens. Carter and Caler (2) derived their model from creep data in which, for any specimen, strain and time are measured, but stress is constant. Because bone behaves almost linearly until it yields, imposing a constant strain rate is, up to the yield point, the equivalent of imposing a constant stress rate. After the yield point, the strain rate would remain the same, but the stress rate would fall to much lower values. It is possible to approximate a strain rate equation from a stress rate equation, as Carter and Caler have done, by dealing with the linear part of the curve only.

The information in the present data allows us to see the effect of considering yield stress, as opposed to ultimate tensile strength, on the validity of Carter and Caler's model (relevant equations: A6–A10). Clearly, the equations are very similar indeed to equivalent equations 1–5, for ultimate tensile stress. This result is to be expected, since usually the stress at fracture is very little more than the yield stress. It is satisfactory, however, that the model is able to account for yield stress just as well as it can for ultimate tensile strength.

Yield Strain and Young's Modulus

The model of Carter and Caler makes no explicit predictions concerning the strain at which yield or fracture occur. Fracture strain is dependent on various adventitious features, including how well machined the specimen is, and is unlikely to be modeled easily. Yield strain, however, is an important variable to model, because different and important conclusions can be drawn according to whether it is strain-rate dependent. It follows from *geometrical* considerations that the yield stress and, because it is never very much greater than yield stress, the ultimate tensile strength, are proportional to the product of yield strain and Young's modulus of elasticity. An increased value for yield stress could therefore be produced, geometrically, either by an increase in the Young's modulus, with the value of yield strain unchanged, or by an increase in the yield strain, with the value of Young's modulus unchanged, or, by some combination of these. Equations A12–A15 show that yield strain is strongly loading-rate dependent.

Although Carter and Caler's 1985 article is not concerned with Young's modulus, in their 1983 article they produce evidence that Young's modulus is strain rate dependent. Their equations are:

$$\sigma_{\text{ult}} = 147\dot{\epsilon}^{0.055} \text{ (as above) and}$$

$$E = 21.4\dot{\epsilon}^{0.050}$$

They state

> A comparison of (the equations) suggests that strain rate may have a slightly greater effect on strength than on modulus. Considering the degree of data scatter, however, this difference may be difficult to experimentally confirm.

The present data suggest, however, that the value of Young's modulus is barely if at all dependent on loading rate (equations A17–A20). Taking either stress rate or strain rate as the sole independent variable, the effects of strain rate and stress rate on Young's modulus are statistically significant but rather small (equations A17 and A18). Equation A17 shows that increasing the strain rate by a factor of 10^3 apparently increases Young's modulus by 24%. Young's modulus is, however, as shown by equation A16, very dependent on the mineral content of the specimen. Equation A16 implies that an increase in the mineral content over the range of the present data will increase Young's modulus by 75%. There was a nonsignificant correlation between mineral and loading rate and, if the effect of mineral on Young's modulus is excluded, the effect of increasing the loading rate by a factor of 10^3 is only 11% (equation A19). This effect is statistically insignificant; even if it were significant, however, it would be much less important than the increase of 39% in yield stress for a corresponding increase in loading rate.

For any particular test, the stress at yield should be the product of Young's modulus and yield strain. The equation relating strain rate to yield stress (equation A9) is close to the product of equations A14 and A19, which is as it should be.

This analysis, if of general applicability, shows that loading rate has, over the range of the present data, little effect on Young's modulus, and that the positive relationship between loading rate and yield and ultimate strength is produced by the effect of loading rate on *yield strain*.

DISCUSSION

The questions posed previously in relation to Carter and Caler's data might be answerable by the present data. We can now consider them in turn.

Are the Results Generally in Agreement?

The results discussed here refer only to monotonically increasing loading. Also, they do not extend to such high strain rates as were used by other workers considered by Carter and Caler. They refer to bovine bone specimens tested at room temperature, rather than human bone at 37°C. Carter and Caler used specimens in which the variation of mineral content was unkown but probably small. In the present data, the mineral content varied considerably and had a marked effect on mechanical properties. It is satisfying, therefore, that when the effects of mineralization are excluded, the effects of loading rate are similar.

Carter and Caler's equation using strain rate as the explanatory variable is $\sigma_{ult} = 147\dot{\epsilon}^{0.055}$. The equivalent equation for the present data, taking a median value for mineral of 66% is:

$$\sigma_{ult} = 177\dot{\epsilon}^{0.067}$$

Take as a null hypothesis that the two exponents, 0.055 and 0.067, do not differ. Carter and Caler's exponent is derived by so much back calculation that one cannot assign a SE to it. The SE for the present data (0.0097), however, though quite small, produces a lower expected bound of 0.051 with p of 0.10. (It is even lower if we take $p = 0.05$.) This lower bound of 0.051 is lower than the value of Carter and Caler, thus, the two exponents cannot be taken to be different.

It is not surprising that the values for the present data produce estimates of tensile strength if anything somewhat greater than those of Carter and Caler. They refer to cow's bone, which is stronger than the human bone (3) used by Carter and Caler, and the tests were carried out at room temperature, which may slightly increase strength as compared with tests at body temperature (3), which was used by Carter and Caler.

Does Yield Stress Behave Differently From Ultimate Tensile Strength?

In the experiments producing the present data, yield stress was measured as well as strength. These values were always similar, and the equations describing them (equations A1–A5 vs. A6–A10) are virtually identical.

Does Inferring Strain Rate From Stress Rate Vitiate the Results?

Measured values of Young's modulus varied by a factor of ~2 in the present data; thus, inferring strain rate from stress will produce errors of similar magnitude. Because of the very large range of strain rates actually used (three orders of magnitude) we should expect such error to be trivial. The present data produce virtually identical exponents for both strain rate and stress rate, and we can conclude that inferring strain rate from stress rate is perfectly satisfactory given the range of Young's modulus likely to be encountered in practice. Inferring strain rate from stress rate is not permissible in the postyield region, but that is not really an issue here because the fracture stress is rarely very little more than the yield stress.

Will Ignoring Mineral Content Vitiate the Results?

If strain rate and mineral content are uncorrelated, ignoring mineral content clearly cannot produce a *bias* in the results. Small variations in mineral content have a large effect, however, as compared with large variations in strain rate. Any fortuitous relationship between strain rate and mineral content therefore is likely to produce results that give quite a poor idea of the relationship between strain rate and other mechanical variables. This is shown in the present data. The apparent exponent relating strain rate and ultimate tensile strength was 0.090, greater than Carter and Caler's value of 0.055. When the effect of mineral was excluded, however, the exponent fell to 0.067. The implications of this are that calculated relationships between mechanical properties and strain rate will be secure only if mineral content is taken into account or if there is little variation in mineral content.

Can Further Information be Obtained From Young's Modulus and Yield Strain?

Because bone is known to be a viscoelastic material, it is surprising that Young's modulus seems to be hardly dependent on strain rate according to the present data. Some workers have found such a strain rate dependence, for instance, Wright and Hayes (13). These demonstrations, however, depend on some extremely high strain rates to demonstrate an effect. The work of Wright and Hayes, for instance, used a maximum strain rate of 237 s^{-1}. Assuming a strain at failure of 1%, this implies failure in $\sim 4 \times 10^{-5}$ s, which is surely far shorter than the time to failure in clinical situations. Other workers, e.g., Crowninshield and Pope (7) found only an extremely weak relationship.

The present data show quite clearly that the higher strengths occurring at higher strain rates are associated with higher yield strains. Carter and Caler do not consider yield strain in the discussion of their model, for they did not measure it. Do the findings from the present data accord with their model? They certainly do. The present data imply that Young's modulus is barely strain-rate dependent; therefore, the stress in any specimen is effectively proportional to the strain. The model assumes that a specimen fails when it has accumulated sufficient damage and that damage accumulates at a rate proportional to some power of the strain (stress) at any time, and proportional to the (infinitesimal) time that the bone is loaded to that strain. The model predicts, therefore, that the specimen loaded quickly will not have accumulated a fatal amount of damage by the time it has reached a strain that will be fatal to a more slowly loaded specimen. Carter and Caler's implied prediction can be set against the suggestion of Frankel and Burstein (10) that bone fails when it has reached a certain strain.

CONCLUSION

The object of this study was to test the cumulative damage model of Carter and Caler for bone fracture insofar as it applies to monotonic loading. The model survives the test well, in that most of the findings reported here are consonant with what would be expected according to the model. Some parts of the test, however, are more severe than others. For instance, the finding that the model predicts yield stress just as well as it predicts fracture stress is satisfactory, because yield shows when large and irreversible changes are occurring in the specimen. It is not a strong test, however, because in bovine bone fracture takes place at a stress little higher than the yield stress; therefore, a model predicting one would be likely to predict the other.

The finding that ignoring mineral content did not matter is also satisfactory. That small changes in mineral do have a marked effect, however, on ultimate tensile strength shows that Carter and Caler (2) were fortunate in obtaining such a clear relationship between stress and time to failure in their creep tests.

The finding from the present data that yield strain increases with loading rate and that so much of the variance in yield strain is explained by loading rate (equations A14 and A15) is a strong test of the model. It is a strong test because it differentiates the Carter and Caler model from another, reasonable model: that fracture is determined by strain. High loading rates are known to make specimens apparently stronger. Bone, being a viscoelastic material may have been failing at some particular strain, and the higher fracture stress may have been caused by the bone having a higher apparent Young's modulus. The present data favour Carter and Caler's model to this alternative one.

Acknowledgment: I wish to thank Dr. J. Bryant for his helpful criticism. This work was supported by SERC grant No. GR/DO4076.

APPENDIX

Various equations derived from the present data

A1. $\sigma_{ult} = 1.26 \times 10^{-12} \times \underset{(6.79)}{\mathrm{Min}^{7.7}}\ (r^2 = 0.58)$

A2. $\sigma_{ult} = 192 \times \underset{(5.58)}{\dot{\epsilon}^{0.090}}\ (r^2 = 0.49)$

A3. $\sigma_{ult} = 78 \times \underset{(6.24)}{\dot{\sigma}^{0.091}}\ (r^2 = 0.54)$

A4. $\sigma_{ult} = 9.64 \times 10^{-10} \times \underset{\substack{(8.13)\\ [0.76]}}{\mathrm{Min}^{6.2}} \times \underset{\substack{(6.90)\\ [0.0097]}}{\dot{\epsilon}^{0.067}}\ (r^2 = 0.83)$

A5. $\sigma_{ult} = 1.87 \times 10^{-9} \times \underset{\substack{(7.85)\\ [0.75]}}{\mathrm{Min}^{5.9}} \times \underset{\substack{(7.30)\\ [0.0093]}}{\dot{\sigma}^{0.067}}\ (r^2 = 0.84)$

A6. $\sigma_y = 1.38 \times 10^{-12} \times \underset{(6.90)}{\mathrm{Min}^{7.7}}\ (r^2 = 0.59)$

A7. $\sigma_y = 184 \times \underset{(5.57)}{\dot{\epsilon}^{0.089}}\ (r^2 = 0.48)$

A8. $\sigma_y = 75 \times \underset{(6.27)}{\dot{\sigma}^{0.091}}\ (r^2 = 0.54)$

A9. $\sigma_y = 9.49 \times 10^{-10} \times \underset{(8.34)}{\mathrm{Min}^{6.2}} \times \underset{(6.98)}{\dot{\epsilon}^{0.066}}\ (r^2 = 0.84)$

A10. $\sigma_y = 1.87 \times 10^{-9} \times \underset{(8.12)}{\mathrm{Min}^{5.9}} \times \underset{(7.48)}{\dot{\sigma}^{0.067}}\ (r^2 = 0.85)$

A11. $\epsilon_y = 1.90 \times 10^{-8} \times \underset{(3.23)}{\mathrm{Min}^{3.0}}\ (r^2 = 0.24)$

A12. $\epsilon_y = 6.98 \times 10^{-3} \times \underset{(5.77)}{\dot{\epsilon}^{0.055}}\ (r^2 = 0.50)$

A13. $\epsilon_y = 4.06 \times 10^{-3} \times \underset{(5.67)}{\dot{\sigma}^{0.053}}\ (r^2 = 0.49)$

A14. $\epsilon_y = 2.25 \times 10^{-6} \times \underset{(2.66)}{\mathrm{Min}^{1.9}} \times \underset{(5.26)}{\dot{\epsilon}^{0.048}}\ (r^2 = 0.59)$

A15. $\epsilon_y = 2.66 \times 10^{-6} \times \underset{(2.34)}{\mathrm{Min}^{1.8}} \times \underset{(4.91)}{\dot{\sigma}^{0.046}}\ (r^2 = 0.57)$

A16. $E = 5.25 \times 10^{-5} \times \underset{(6.03)}{\mathrm{Min}^{4.8}}\ (r^2 = 0.52)$

A17. $E = 2.62 \times 10^{4} \times \underset{(2.26)}{\dot{\epsilon}^{0.031}}\ (r^2 = 0.13)$

A18. $E = 1.89 \times 10^{4} \times \underset{(2.76)}{\dot{\sigma}^{0.035}}\ (r^2 = 0.19)$

A19. $E = 2.22 \times 10^{-4} \times \underset{(5.46)}{\mathrm{Min}^{4.4}} \times \underset{(1.41\ \mathrm{NS})}{\dot{\epsilon}^{0.015}}\ (r^2 = 0.55)$

A20. $E = 3.46 \times 10^{-4} \times \text{Min}^{4.3} \times \dot{\sigma}^{0.018}$ ($r^2 = 0.57$)
(5.27) (1.75 NS)

σ_{ult}, ultimate tensile strength in megapascals; σ_y: stress at yield in megapascals; ϵ_y: strain at yield; E: Young's modulus of elasticity in megapascals; Min, mineral content, determined by percentage weight left after ashing; $\dot{\epsilon}$: strain rate in reciprocal seconds; $\dot{\sigma}$: stress rate in megapascals per second; r^2: square of the correlation coefficient between the dependent and all the explanatory variables; this is a measure of how much of the variance in the dependent variable is "explained" by the explanatory variables; NS: not statistically significant. Numbers in parentheses below the values for mineral, strain rate, and stress rate are the *t* values. With 33 *df*, as here, a value of *t* of 2.04 is significant at 5%, a value of 2.74 is significant at 1%, and a value of 3.60 is significant at 0.1%. The values in square brackets are the SE for those values compared with the values of Carter and Caler (2).

REFERENCES

1. Burstein AH, Reilly DT, Martens M: Aging of bone tissue: Mechanical properties. *J Bone Joint Surg [Am]* 58:82–86, 1976
2. Carter DR, Caler WE: Cycle-dependent and time-dependent bone fracture with repeated loading. *J Biomech Eng* 105: 166–170, 1983
3. Carter DR, Caler WE: A cumulative damage model for bone fracture. *J Orthop Res* 3:84–90, 1985
4. Carter DR, Hayes WC: Compact bone fatigue damage—1. Residual strength and stiffness. *J Biomech* 10:325–338, 1977a
5. Carter DR, Hayes WC: Compact bone fatigue damage: A microscopic examination. *Clin Orthop* 127:265–274, 1977b
6. Carter DR, Caler WE, Spengler DM, Frankel VH: Fatigue behavior of adult cortical bone—The influence of mean strain and strain range. *Acta Orthop Scand* 52:481–490, 1981
7. Crowninshield RD, Pope MH: The response of compact bone in tension at various strain rates. *Ann Biomed Eng* 2:217–225, 1974
8. Currey JD: The mechanical consequences of variation in the mineral content of bone. *J Biomech* 2:1–11, 1969
9. Currey JD: The effects of strain rate, reconstruction and mineral content on some mechanical properties of bovine bone. *J Biomech* 8:81–86, 1975
10. Frankel VH, Burstein AH: *Orthopaedic Biomechanics*. Philadelphia, Lea and Febiger, 1970
11. Preuschoft H: On the quality and magnitude of mechanical stresses in the locomotor system during rapid movements. *Zeit Morph Antrop* 75:245–262, 1985
12. Rubin CT, Lanyon LE: Limb mechanics as a function of speed and gait: A study of functional strains in the radius and tibia of horse and dog. *J Exp Biol* 101:185–191, 1983
13. Wright TM, Hayes WC: Tensile testing of bone over a wide range of strain rates: Effects of strain rate, microstructure and density. *Med Biol Eng* 14:641–679, 1976