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Magnitude of Loads Influences the Site of Failure of Highly Curved Bones

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Abstract

The structure and material properties of bones along with applied boundary conditions determines the region of peak stresses, where fracture is expected to occur. The magnitude of the applied load does not influence the site of peak stresses, and, as a result, the fracture site is not expected to change during fatigue loading of whole bone at different loads. However, in a highly curved bone such as the rat ulna, the magnitude of applied loads was found to influence the fracture site. Fatigue loading was conducted under load control on intact rat forearms and on excised ulnae. The distance to the site of failure from the proximal olecranon process of ulnae was determined. In intact forearms, the site of failure demonstrated a linear progression distally, towards sites with lower moment of inertia (or sites exhibiting lower section modulus). Intact rat forearms and excised ulnae loaded to failure at low loads fractured 2mm to 3mm distal to where they failed when applying high loads. This indicates a shift in the site of failure by approximately 10% of whole bone length just by varying the applied load magnitude. Qualitatively, failure occurred more distally at low loads in the excised ulnae in comparison to loading of the intact forearm. The site of failure in excised ulnae were similar when loading at 2Hz or at 4Hz, suggesting that this was frequency independent in this range and indicating strain rate was not an important contributing factor. Creep loading of excised ulnae also demonstrated similar changes in the site of failure, indicating that magnitude of loads, and not type of loading, were important in determining the site of failure. Times to failure decreased when frequency of loading was higher and were further lowered with creep loading. This has important implications with regards to the volume of bone that undergoes damage under physiological loading, before it fails.

Keywords

Rat Forearm Compression Loading; Ulnar Failure; Fatigue; Shift in Fracture Site; Moment of Inertia

1. Introduction

Bones adapt to mechanical loading to attain structures that are resistant to applied loads given local constraints related to anatomy and growth and within the framework of evolutionary challenges (Currey, 2003; Diogo et al., 2013). As a result, the shape of whole

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bone can be such that failure occurs at sites other than the smallest cross-section and/or smallest moment of inertia. This is especially true for curved bones such as the ulnae and tibiae of commonly used rodent strains. Finite element analysis of the ulna indicates that the site for peak strains co-localizes to the site of damage, a region that does not exhibit the smallest cross-sectional area or moment of inertia (Kotha et al., 2004). Based on linear, elastic finite element analysis, the site of failure should be similar irrespective of load magnitude as long as the direction of loading is not changed. However, because the cross-section/moment of inertia of the ulna becomes relatively smaller at the distal end (at least 5 times lower than at the mid-shaft), we investigated whether the site of failure would be dependent on applied loads. Specifically, we test the hypothesis that the site of failure should not change with the magnitude of applied loads.

2. Methods

All experiments were conducted with IACUC approval. Rats (6-month old, female, Sprague-Dawley) were euthanized by carbon dioxide inhalation after being received. Their weights were measured after sacrifice. A total of 27 rats were used in these experiments. Fatigue and creep loading to failure were conducted under load control using a Bose Enduratec 3300 or a custom loading machine (Macione et al., 2012) with a 100N load cell with $\pm 0.01\text{N}$ resolution and displacement resolution of $\pm 1\text{ }\mu\text{m}$ (Minnetonka, MN).

Fatigue loading of whole forearms: Both forearms of 9 rats were excised and fatigue loading was conducted to failure while keeping the forearms moist and in 0.1% sodium azide (2Hz, haversine waveform, high load to -0.3N). Loading was conducted by placing the forearm in between two brass U-cups (Torrance et al., 1994). The olecranon process at the proximal end of the ulna is held fixed (left side of Fig. 1), while load is applied to the styloid process of the ulna and the radius at the distal end (right side of Fig. 1). Under this loading, the natural curvature of the ulna, causes bending in two directions, resulting in compressive strains on the medial surface and tensile strains on the tensile surface. Peak compressive loads ranged between 26N to 14N and tests were conducted in increments of 1N to 2N. The numbers of cycles to failure were recorded. After failure, the remnant humerus and soft tissues were removed and x-ray micrographs were taken to identify distance of the failure site from the proximal olecranon process. The distance of the fracture site from the proximal olecranon process was also determined using a vernier caliper (± 0.01 resolution). Statistical analysis was performed to evaluate if the slope of the line (Load versus Distance to the site of failure from the proximal end) was different from zero.

Creep and Fatigue loading of excised ulnae: Ulnae were excised from 18 additional animals, cleaned of soft tissue, placed in calcium buffered saline containing 0.1% sodium azide and loaded to failure at high loads (18N) or at low loads (10N). Note that a fraction of the applied load is transferred through the radius in the intact forearm, and, therefore the loads used for loading excised ulnae are lowered. The loads used were expected to be equivalent to loading of whole forearms at 14N and 26N respectively (Kotha et al., 2004). Loading was conducted by placing the excised ulnae between brass U-cups, with the load being applied in the direction parallel to the length of the ulna (left-to-right in Fig. 1). During this loading, the natural curvature of the ulna cause bending induced tensile and compressive stresses on the lateral and medial surfaces, respectively (Kotha et al., 2004). Loading was conducted at two different frequencies, 2Hz or 4Hz (haversine waveform, high load to -0.3N), to evaluate if the loading rate was a factor in determining the site of failure. Loading at higher frequency and low loads (4Hz at 10N) should increase the loading rate beyond those generated when loading at lower frequency and high load (2Hz at 18N). Creep loading was also performed at the high (18N) and low (10N) loads to evaluate the role of creep in determining the site of failure and the duration at which failure occurs. The number of cycles to failure (fatigue

loading) and the time to failure (creep loading) were recorded. Numbers of cycles to failure were converted to time to failure based on the loading frequency. Distances to the site of failure from the proximal olecranon process were measured using a vernier caliper (± 0.01 resolution). Two-way Anova was performed followed by Tukey's significant difference tests to determine if the loading frequency or the magnitude of loading affected the site of failure.

3. Results

The site of failure shifted distally by approximately 2mm as the peak compressive load used for fatigue loading changed from 26N to 14N as observed using x-ray micrographs (Fig. 1). It is also observed that failure occurs at a larger cross-section at higher loads than at lower loads. There are also differences in the pattern of failure in the radius (though this was not investigated because the sites of fracture initiation were not clear – Fig. 1).

In figure 2, a gradual shift is observed as the site of failure of the ulna moves from 15.2mm to 17.3mm as the peak compressive load decreases from 26N to 14N, respectively ($p < 0.001$). There was a linear progression in the numbers of cycles to failure as load was increased, with failure occurring in a few cycles at the high loads and at millions of cycles at the low loads.

Creep loading and cyclic loading, irrespective of frequency of loading, resulted in failure occurring more distally at lower loads in comparison to the site of failure at high loads (Fig. 3). During cyclic loading, the site of failure shifted from 58.6 ± 1.3 % of total ulna length at high loads towards 68.8 ± 2.2 % at low loads (as measured from the olecranon process – left side of Fig. 1; data for both frequencies are combined) ($p < 0.001$). Results were similar when excised ulnae were loaded in creep at high and low loads (Fig. 3). The site of failure shifted from 58.1 ± 3.2 % of total ulna length at high loads to 67.0 ± 3.8 % at lower loads ($p < 0.001$). When comparing site of failure in excised ulnae to that of the entire forearm, qualitative differences were observed at lower loads, with failure occurring more distally in the excised ulnae.

Failure occurred at extremely short time scales at high loads, and at considerably longer time scales when loading at low loads (Fig. 4). When loading at high loads, times to failure were not dependent on loading frequency or mode of loading (creep or cyclic). When loading at low loads, the time it took for the bones to fail decreased with increased frequency of cyclic loading ($p < 0.001$) and was the shortest during creep loading ($p = 0.03$). During cyclic loading, failure occurs in fewer cycles at greater loads ($p < 0.001$), irrespective of the frequency of loading (Fig. 5). At the same loads, loading at a higher frequency (2Hz vs 4Hz), there was no difference in the numbers of cycles to failure when loading was conducted at different frequencies (2Hz or 4Hz).

4. Discussion

The results do not support the hypothesis that the site of failure remains the same irrespective of the load magnitude used during cyclic loading to failure of a highly curved bone such as the rat ulna. A shift in the site of failure is unexpected because linear, elastic, computational finite element analysis indicates that the site of peak strains within the whole bone occur at the same site, irrespective of the load magnitude used. Therefore, the significance of these experiments is in demonstrating that sites of failure are dependent on magnitude of loading for highly curved bones such as the rat ulna.

The site of failure moved distally by approximately 10% of the ulna length, towards sites exhibiting low moment of inertia. Yet, even at the low loads used in this study, where bones failed after millions of cycles of loading, failure did not occur in the cross-section exhibiting

the smallest moment of inertia. Note that for these bones, the sites with smallest moment of inertia are also the sites exhibiting the smallest section modulus. Also note that when whole bones are loaded in axial compression (i.e. along the long axis of the bone), the site with the smallest section modulus is close to the site with the largest moment arm to the applied compressive load, resulting in a large bending moment. Because of this, it was expected that damage would accumulate and cause failure to occur at the site with the lowest section modulus (or moment of inertia). Based on damage based finite element models (Taylor et al., 2002; Taylor et al., 1999), we postulate the following to explain the observed shift in site of failure based on the magnitude of applied loads. As peak strains occur at the same site irrespective of magnitude of loading, this indicates that damage at the site of peak strains induces changes in local material properties. This in turn causes a change in stress distribution within the whole bone resulting in the site of peak strains moving distally. After this new site experiences a loss of material properties as a result of damage accumulation, the pattern of changing stress distribution within the material repeats until at a particular site damage accumulates rapidly and the bone fails. A shift in site of failure by 2mm to 3mm indicates that a substantial region of whole bone is affected by damage. Note that this shift in site of failure by 10% of whole bone length in a rat ulna is equivalent to a 2cm shift in an adult human. This means that in situations where bone adaptation due to new bone formation is severely inhibited, such as the elderly – physiological loading of highly curved structures, such as the femoral neck or vertebral spinous processes, among others, may result in a large volume of bone becoming deleteriously compromised mechanically before fracture occurs.

Loading of excised ulnae at different frequencies, at 2Hz or at 4Hz, did not alter the site of failure. Initial strain rates estimated from previous strain gage measurements in our laboratory indicate that at low loads, peak strain rates changed from 0.012s^{-1} to 0.025s^{-1} as frequency was increased from 2Hz to 4Hz. Correspondingly, at the higher loads, peak strain rates changed from 0.022s^{-1} to 0.048s^{-1} as frequency was increased. As changes to the site of failure were not observed with changes in strain rates, strain rates in this range can be ruled out as a major influence in the observed shift in the site of failure. This is expected because damage initiation and accumulation is highly dependent on stress magnitudes as compared to strain rates (Cotton et al., 2005; Winwood et al., 2006).

As expected, loading at high loads causes bones to fail in shorter times (within 30 seconds) as opposed to loading at low loads (periods of a week or two). When loading at high loads, loading frequency or mode of loading did not affect time to failure. In contrast, when loading at low loads, a higher frequency of loading causes whole bones (ulnae) to fail in shorter time, while creep loading caused failure at even shorter times. It is noted that failure in bones is thought to result from damage phenomena that are time- or cycle-dependent (Caler and Carter, 1989; Carter and Caler, 1983, 1985). This suggests that during creep loading, there is significantly greater time-dependent damage in comparison to cycle-dependent damage (at the frequencies used) (Pattin et al., 1996). Note that samples experience twice the time-averaged load magnitudes during creep loading as opposed to when they are loaded using a haversine waveform. When cyclic loading at higher frequencies (4Hz), failure may occur earlier, as strain rate dependent damage accumulation is greater in comparison to loading at lower frequency (2Hz) (Cotton et al., 2005; Zioupos et al., 2008).

The site of failure was qualitatively observed to shift more distally when loading the whole forearm as opposed to when loading excised ulnae. This may be due to changes in stress transfer characteristics between the radius and ulna during loading of the whole forearm (Kotha et al., 2004; Lu et al., 2012) which may be affected by damage accumulation in the ulna. It is noted that because of stress transfer between the radius and the ulna in whole

bone, loading of excised ulnae at 10N and 18N would be equivalent to loading of whole bones at 14N and 26N, respectively (Kotha et al., 2004). Qualitatively, the site where the radius failed also demonstrated a shift in the site of failure. However, the cross-section of failure of the radius was not as clear as that observed in the case of the ulna (Fig. 1). This indicates that damage accumulation in one bone (the ulna) affects the pattern of stress transfer in the adjacent structure and causes failure of the adjacent bone (the radius) at different sites.

A limitation of the current study is that damage after different cycle numbers were not evaluated experimentally, especially when loading to low loads. Another limitation is that loading was not performed at loads lower than 10N for excised ulna (14N for whole bone). This latter limitation prevented us from determining whether bones were designed so that failure can occur at the cross-section with the smallest moment of inertia. Another limitation is that off-axis loads were not measured, but, are expected to be small in comparison to the applied longitudinal loads (Kotha et al., 2004).

5. Conclusion

The site of failure is observed to shift distally, towards sites exhibiting smaller moment of inertias, during fatigue or creep loading of highly curved structures, such as the intact rat forearm or excised rat ulna. This suggests that a substantial portion of whole bone can accumulate damage when loading at loads in the physiological range before failure occurs.

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References

- Caler WE, Carter DR. Bone creep-fatigue damage accumulation. *J Biomech.* 1989; 22:625–635. [PubMed: 2808445]
- Carter DR, Caler WE. Cycle-dependent and time-dependent bone fracture with repeated loading. *J Biomech Eng.* 1983; 105:166–170. [PubMed: 6865359]
- Carter DR, Caler WE. A cumulative damage model for bone fracture. *J Orthop Res.* 1985; 3:84–90. [PubMed: 3981298]
- Cotton JR, Winwood K, Zioupos P, Taylor M. Damage rate is a predictor of fatigue life and creep strain rate in tensile fatigue of human cortical bone samples. *J Biomech Eng.* 2005; 127:213–219. [PubMed: 15971698]
- Currey JD. How well are bones designed to resist fracture? *J Bone Miner Res.* 2003; 18:591–598. [PubMed: 12674319]
- Diogo R, Linde-Medina M, Abdala V, Ashley-Ross MA. New, puzzling insights from comparative myological studies on the old and unsolved forelimb/hindlimb enigma. *Biol Rev Camb Philos Soc.* 2013; 88:196–214. [PubMed: 22958734]
- Kotha SP, Hsieh YF, Strigel RM, Muller R, Silva MJ. Experimental and finite element analysis of the rat ulnar loading model-correlations between strain and bone formation following fatigue loading. *J Biomech.* 2004; 37:541–548. [PubMed: 14996566]
- Lu Y, Thiagarajan G, Nicolella DP, Johnson ML. Load/strain distribution between ulna and radius in the mouse forearm compression loading model. *Med Eng Phys.* 2012; 34:350–356. [PubMed: 21903442]
- Macione J, Nesbitt S, Pandit V, Kotha S. Design and analysis of a novel mechanical loading machine for dynamic in vivo axial loading. *Rev Sci Instrum.* 2012; 83:025113. [PubMed: 22380131]
- Pattin CA, Caler WE, Carter DR. Cyclic mechanical property degradation during fatigue loading of cortical bone. *J Biomech.* 1996; 29:69–79. [PubMed: 8839019]

- Taylor M, Cotton J, Zioupos P. Finite element simulation of the fatigue behaviour of cancellous bone. *Meccanica*. 2002; 37:419–429.
- Taylor M, Verdonchot N, Huiskes R, Zioupos P. A combined finite element method and continuum damage mechanics approach to simulate the in vitro fatigue behavior of human cortical bone. *J Mater Sci Mater Med*. 1999; 10:841–846. [PubMed: 15347962]
- Torrance AG, Mosley JR, Suswillo RF, Lanyon LE. Noninvasive loading of the rat ulna in vivo induces a strain-related modeling response uncomplicated by trauma or periosteal pressure. *Calcif Tissue Int*. 1994; 54:241–247. [PubMed: 8055374]
- Winwood K, Zioupos P, Currey JD, Cotton JR, Taylor M. The importance of the elastic and plastic components of strain in tensile and compressive fatigue of human cortical bone in relation to orthopaedic biomechanics. *J Musculoskelet Neuronal Interact*. 2006; 6:134–141. [PubMed: 16849822]
- Zioupos P, Hansen U, Currey JD. Microcracking damage and the fracture process in relation to strain rate in human cortical bone tensile failure. *J Biomech*. 2008; 41:2932–2939. [PubMed: 18786670]

Figure 1.

Location of failure in the curved ulnar bone shifts as a function of load magnitude. Higher loads result in failure occurring in the more proximal and larger cross-section. The distance to the fractured site is measured from the proximal olecranon process (which lies to the left vertical edge in the figure).

Figure 2.

During fatigue loading of the rat forearm, as load is increased, the numbers of cycles to failure go from millions of cycles at 14N to tens of cycles at 26N. Simultaneously, the site of failure shifts proximally as the load is increased from 14N to 26N.

Figure 3.

In excised ulnae, the site of failure shifted distally as the load was decreased, with failure occurring slightly distal to the mid-shaft at high loads and even more distally at lower loads, irrespective of the frequency of cyclic loading (2Hz or 4Hz) or the mode of loading (creep or cyclic).

Figure 4.

In excised ulnae, failure occurs within 30 seconds at high loads (18N) and is not dependent on frequency or mode of loading (creep or cyclic). When loading at low loads, bones loaded in creep loading fail in the shortest times, followed by those loaded at 4Hz and finally by those loaded at 2Hz. Groups with different letters are statistically different ($p < 0.05$).

Figure 5.

In excised ulnae, failure occurs in fewer cycles at greater loads. At the same loads, loading at a higher frequency (2Hz vs 4Hz), did not affect the numbers of cycles to failure. Groups with different letters are statistically different ($p < 0.001$).