The University of New Mexico

The Effect of Normal Loading on Bone Curvature

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Background:

Bone curvature has long been thought to be an indicator of life activity amongst hominids according to anthropologists. Studies have been done on bone curvature in fossils based on the idea that curvature is influenced by functional loading (use during life). Bone curvature affects how loading stresses are distributed amongst long bones as well as their magnitude. (Swartz, 1990) A common thought is that the bones that exhibit more curvature are inferred to have been loaded more, meaning higher activity levels during life. However, it's recently been suggested that curvature is influenced more so by genetics rather than life activity.

Bone physiology has been studied extensively over the past century. It has been shown that bone modeling and remodeling are done on the cellular level. Osteocytes are cells in the bone matrix that sense the amount of loading or lack of. Increased amounts of loading cause the osteocytes to send a signal to osteoblasts, cells that assist in forming new bone. If there is a lack of loading, osteocytes send signals to osteoclasts who then will assist in resorbing the bone. (Isojima and Sims, 2021). Wolff's law was one of the first theories to assess how bone changes in response to stimuli. It states that bones' internal architecture will change in predictable ways in response to mechanical stimuli. (Frost, 1993) Greater mechanical loading will result in denser bones, and less loading will result in less dense bones. However, this frame does not complete the whole picture regarding bone physiology and is sometimes not applicable. This is because Wolff's law does not take into account other characteristics of bone such as curvature. In fact, according to engineering principles used by Wolff, naturally curved bones such as the tibiae, radii, and ulnae are more prone to failure. By Wolff's law, those bones should be subject to straightening as straighter bones accrue more strength. (Javaheri et al., 2020) This is obviously not the case begging the question of what affects curvature. The mechanostat theory attempts to elaborate on Wolff's law. It proposes a "strain-controlled feedback loop" in which formation and resorption are continually acting processes based on environmental loading. This posits that a basal bone architecture will be returned once habitual loading ceases. Meaning, the lasting effects of loading are not examined by this theory. (Frost, 1998)

If the curvature of bones decreases mechanical strength, natural selection would remove this trait from the population. Yet, why does it persist? The answer could be bending predictability. In bones that are more prone to predictable bending patterns, it is hypothesized that they will form curvature patterns consistent with bending. (Bertram and Biewener, 1988; Jade et al. 2014) According to Bertram and Biewener (1988), bone curvature is determined by peak loads the bone experiences relative to the bone tissue limits and a degree of variability in loading orientation during the normal range of activity. This means that if a bone experiences a more predictable loading orientation compared to loading magnitude it will prefer a more curved shape. On average, the majority of curvatures will decrease load-carrying capacity. This presents an evolutionary trade-off: bending predictability vs mechanical strength. For bones that experience high rates of consistent bending patterns, it tracks that they would favor a curvature allowing for bending predictability. This will reduce the strain the bone experiences allowing it to operate more efficiently. For bones that experience unpredictable bending patterns, it tracks that they would favor mechanical strength. This will allow these bones to undertake the strain of multiple types of bending without fracture or buckling.

Chimpanzees are known to have pronounced curvature in their phalanges assisting in their arboreal locomotion. Did their genetics cause this curvature or their environmentally driven arboreal activity? Past thought believed that arboreal activity came first, but is that the reality? The answer to this question begins with a rare case study of a chimpanzee raised very much like a human. Gertrude Lintz, a New York City socialite and exotic animal owner in the 1930s, captured an infant chimpanzee, Suzy, from wild Africa. Lintz raised Suzy very much like a human child meaning she experienced no to very little arboreal activity. Advocates of environmental effects on bone curvature would expect Suzy to have less marked phalangeal curvature compared to a wild chimpanzee. Wallace et al found the opposite, interestingly enough. Suzy's curvature was equivalent to that of wild chimpanzees and outside the range of modern humans. (Wallace, 2020) Of course, this sample study of one individual is not enough to claim the total genetic causation of bone curvature. It is also not enough to discredit environmental loading as a cause.

Direct experimental evidence is lacking that routine/normal loading of bones affects curvature. However, there is evidence that extreme loading and unloading can have an effect. Lanyon (1980) measured how very little use of a bone can affect its curvature. A small section of the sciatic nerve was removed using lab mice as a model specimen, making that limb non-weight bearing. He found that bone width, mass, cross-sectional shape, and longitudinal curvature varied between normal limbs and affected limbs. Bone length was the same throughout. In the affected limb there was a decrease in bone width, mass, and curvature. They exhibited a rounded cross-sectional shape. The unaffected limb exhibits a triangular shape. Two hypotheses were proposed for these findings. The Accomodational Hypothesis proposes that muscle activity affects the degree of curvature and cross-sectional shape. Greater use of muscle causes greater curvature and triangular cross-sections to allow for more attachment sites. Removing the ability to use these muscles by removing a portion of the sciatic nerve removes the muscle stimulus and proper development of bone curvature and shape fails to occur. The Bone Strain Hypothesis states that curvature is caused by the pulling of muscle to decrease the amount of bending moments the bone experiences. This will allow greater strain to be loaded on the bone before damage occurs. Overall, Lanyon found that removing the ability to use a limb normally results in failure to develop normal curvature and shape of the bone. (Lanyon, 1980)

Javaheri et al. tested how extreme loading of the tibia of female mice would affect curvature. To test this theory, the control mice would be placed under anesthesia while a loading stress applied through the knee would be induced on their right tibia periodically. The magnitude of the loading stress was more than the average mouse would experience in daily life but less than the point of fracture and buckling. They then used micro-CT technology to measure the tibiae. The results of this study were novel. Bone curvature was found to be an evolutionarily programmed characteristic variable within a limited range. The mice that experienced greater amounts of loading did exhibit some degree of greater tibial curvature shape and greater lasting cortical growth. Extending beyond this, bone curvature was shown to operate at the whole bone level rather than at local strains. (Javaheri et al., 2020)

Methods and Materials:

Both of these studies show how extreme loading or unloading affects curvature. Yet, there is a degree of unrealism to these experiments. In daily life, most loading to bones is not extreme. There have been no studies to date that have measured bone curvature response to normal physiological loading. This is what this study aims to answer. Here, we obtained an experimental sample and a control sample of young female ICR mice. At four weeks old, the experimental mice were treated to 30 mins of running on a treadmill five days a week for four weeks. They ran on a Columbus Instruments Exer-3/6 treadmill at 12 m/min. This is believed to be an accurate indication of normal activity. Control mice were handled though they did not run.

The groups were subject to a 12-hour light and 12-hour dark pattern. Exercise occurred during the light hours. Both groups had free access to food and water. Both groups' cage activity was measured at weeks 2 and 3 of the exercise program to insure similar activity through the use of a 16-chamber Opto-M3 system (Columbus Instruments). In this system, each cage was placed into a monitoring apparatus that cast a grid of infrared beams 1.27 cm2 above the cage floor. Each individual organism was measured on two separate non-running days. Measurements occurred every hour over a 24-hour period. The average amount of times an infrared beam was broken by movement during these observations (not including non-ambulatory repeated motions such as scratching and grooming) quantified cage activity. At eight weeks, both groups of mice were euthanized by CO2 inhalation. Their tibiae and ulnae were recorded using micoCT scan technology. (Wallace et al., 2015)

To measure the actual curvature of these bones, we used a technique similar to the one Swartz (1990) used. The curvature moment arm (C) was used to assess the degree of curvature in the tibiae and ulnae of the experimental and control group. (C) can be measured in both anterior-posterior (AP) views as well as mediolateral (ML) views. Measurements in the AP view will measure ML curvature. By the same token, measurements in the ML view will measure AP curvature. In this study, we measured anteriorly-posteriorly. To obtain (C) we first measure a chord axially between the proximal and distal joints of the long bones. The points of measurement on both the proximal and distal joints are determined to be the midpoint of both the ML and AP cortices. The orthogonal (perpendicular) distance from the maximum point of curvature to the measured chord is (C). The greater (C) is the greater the curvature of the bone. A standardized orientation with respect to anatomical landmarks was utilized in order to have consistency between measurements of different points.

Statistics:

For the tibia, to compare curvature moment arm length between mice in the runner and non-runner groups, we used analysis of covariance (ANCOVA) with activity group as the fixed factor and bone length as the covariate. ANCOVA was necessary for the tibia because curvature moment arm length was found to be positively associated with bone length. For the ulna, curvature moment arm length was not found to be associated with bone length. Thus, curvature moment arm length was compared between activity groups with an independent-sample t-test. Both tests were two-tailed. $P < 0.05$ was considered statistically significant. Analyses were performed in JMP software (version 17).

Results:

For the tibia, in an ANCOVA that included bone length as a covariate, bone curvature moment arm length was not significantly different between runners and non-runners ($P = 0.79$) (Figure 1).

For the ulna, in an independent samples t-test, bone curvature moment arm length was not significantly different between runners and non-runners (P = 0.25) (Figure 2).

Figure 1. Analysis of tibial curvature between runner and nonrunner mice. As you can see here, the differences between the two are not significant.

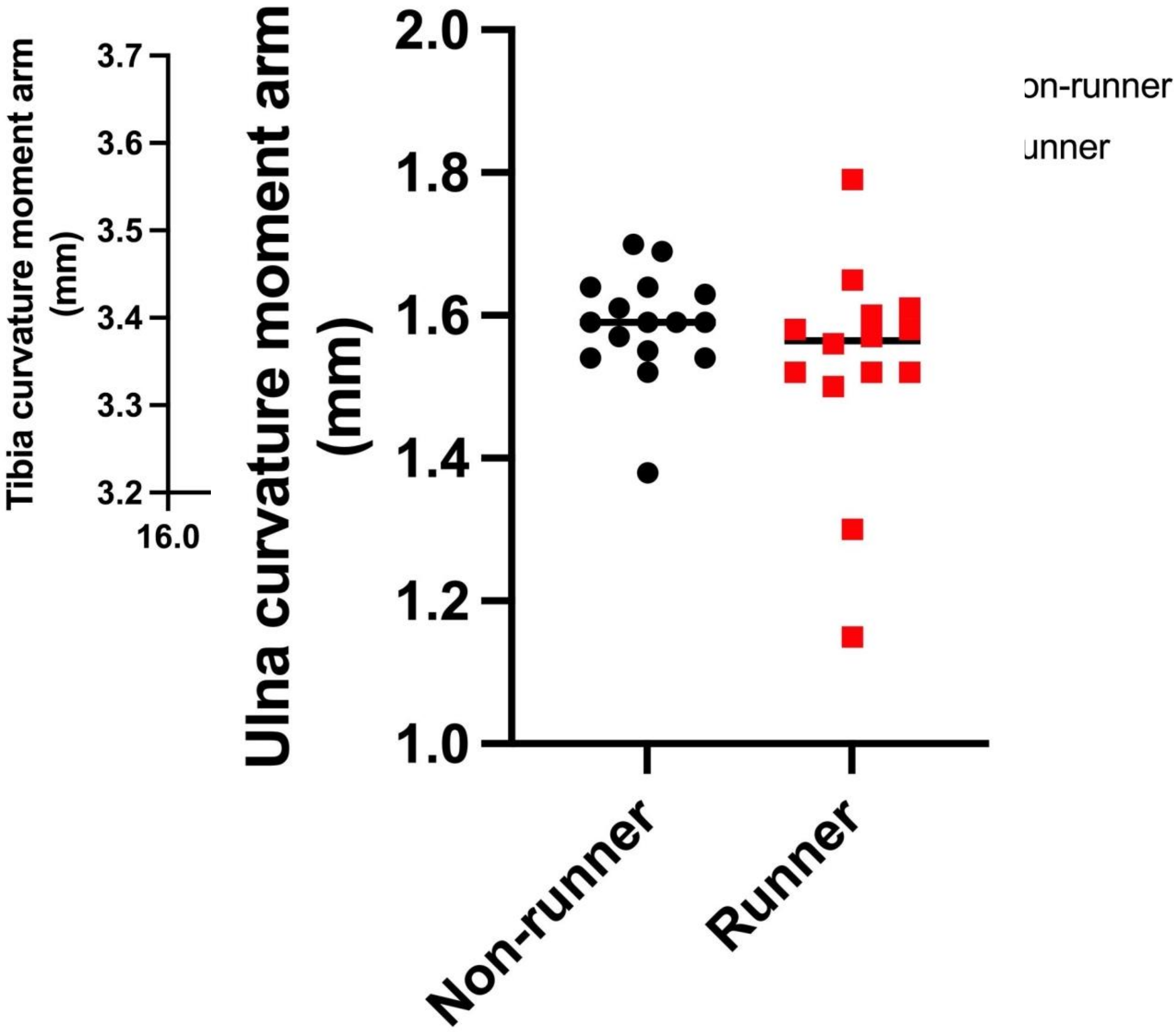

Figure 2. Analysis of the ulnar curvature between the runner and nonrunner mice. Once again, as you can see the results did not differ significantly.

Discussion:

The overall difference in the ulnae and tibiae curvature between the control and experimental groups was not significant. The findings were consistent with Javaheri et al., (2020), long bone curvature seems to have a genetic basis variable within a limited range. Though, this study expands upon this and presents a slightly more realistic view of bone curvature. Studies such as Javaheri et al. (2020) and Lanyon (1980) present extreme alterations in activity that were shown to impact bone curvature to some degree. However, this study mimicked real-life activity patterns, and the resulting difference in bone curvature was not found to be significant. Bone curvature is not found to be affected by activity patterns within a normal physiological range, but it can be affected by abnormal activity patterns. Just as in the case of Suzy the Chimpanzee in Wallace (2020), altering activity patterns of the mice reflected a similar bone curvature to that of the mice with no alterations in activity. This goes against the bending predictability theory proposed by Bertram and Biewener (1988) and Jade et al. (2014). Predictable bending patterns of the running mice did not cause increased curvature of the tibia or ulna when compared to the nonrunning mice. Overall, this study provides evidence to prove that life activity such as exercise does not impact bone curvature significantly. The future implications of this study have the potential to be profound. Anthropologists and other disciplines have been operating under the assumption that curvature is an accurate assessment of life activity. This study disproves that very notion. In doing so, there is a need to re-examine previous information based on this outdated idea.

Works Cited

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