Why is excess body weight associated with greater bone strength?

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ABSTRACT

Excess body weight (overweight, obesity) is known to be associated with greater bone strength. The most common explanation for this phenomenon is that greater body weight engenders greater mechanical loading of bones, which stimulates greater bone formation, leading to greater bone strength. An understudied yet plausible alternative hypothesis is that excess body weight and greater bone strength are associated because both phenotypes result from a common cause: metabolic energy abundance. That is, people who have enough surplus energy to store a lot as adipose tissue may also be able to devote more energy to developing strong bones. Here, we evaluate these two hypotheses using data from 209 adults in the New Mexico Decedent Image Database, a collection of full-body CT scans with associated anthropometric data. Bone strength properties (e.g., cortical area, second moments of area) were quantified in the tibial midshaft from CT scans. Our results provide support for the first but not the second hypothesis. First, we found a significant positive association between body weight and tibial strength after controlling statistically for skeletal frame size (stature and pelvic breadth), suggesting that people who subject their bones to more weight (higher loads) have greater bone strength than explainable solely by their baseline skeletal size. Second, there was not a significant association found between waist circumference and tibial strength after controlling statistically for the effects of body weight, suggesting that people with more adipose tissue (a proxy for energy abundance) do not have greater bone strength than explainable solely by the contribution of adipose tissue to body weight.

INTRODUCTION

Modern human-driven forces like the advancement of technology and industrialization continue to have huge impacts on our bodies. Humans are becoming increasingly unhealthy. This results from a combination of factors including the consumption of calorically dense processed foods and the decreased reliance on walking to get around. Despite obesity being a marked health hazard, it confers some biological benefits. There is evidence in the literature that obesity as a child can cause bone growth to increase, yielding a higher BMD in relation to frame size for obese children (Cao, 2011; Leonard et al., 2011; Vandewalle et al., 2013). Adjusting for frame size, obese children had denser and thus stronger bones than nonobese children. In short, they had greater bone mass.

The most logical explanation for increased bone strength in obese individuals is the increased load imposed on the skeleton by their increased body weight. This increased mechanical loading of bones will cause the body to create more bone to compensate for this increase in load magnitude (Burr et al., 2002). As the body begins to adapt in childhood, the skeleton begins to change and grow stronger. Childhood is where this trend starts, persisting into adulthood (Pearson and Lieberman, 2004). Increased adipose tissue provides for an increase in biomechanical stress on bone. Thus, obesity must lead to an increase in bone strength. The increase in bone formation will then lead to robust skeletal frames in obese individuals compared to nonobese individuals.

An alternative explanation for this hypothesis deals with energy availability. It stands to reason that obese people have access to more energy than nonobese individuals. If the excess energy goes towards the creation of adipose tissue, then they may also be able to store that excess energy in their bones. The human body will use all calories provided to it to grow and reinforce itself, so bone may grow stronger due to an increase in overall energy availability. Surplus energy will be stored throughout the body in many different systems before it will be wasted. Following this logic, an alternative hypothesis could exist that states that obese people experience a greater energy availability, and thus stronger skeletons are made from this excess energy.

Here, we evaluate these two hypotheses using data from about 209 adults from the NMDID, a collection of full-body CT scans associated with anthropometric data. We will attempt to see the effects of increased mechanical loading and energy availability on the benefits of obesity on bone strength.

METHODS AND MATERIALS

The sample consisted of adults in the New Mexico Decedent Image Database (NMDID), a collection of high-resolution full-body CT scans of >15,000 New Mexicans with associated with associated demographic and anthropometric data (Edgar et al., 2020). CT scans and associated information in the NMDID are from people who died since 2010 and whose deaths were investigated by the New Mexico Office of the Medical Investigator, the agency responsible for examining all deaths in the state that do not occur under the care of a physician. All CT scans and associated information are de-identified. None of the individuals' bodies were decomposed at the time of the medical investigator's examination. For all individuals, stature and body weight were measured by the medical investigator. For each individual, data on stature and body weight were used to calculate body mass index (BMI) in kg/m^2 and determine whether they were overweight ($25 \leq BMI < 30$) or obese ($BMI \geq 30$). Waist circumference was measured in the CT scan images at the level of umbilicus using ImageJ software. Pelvis bi-iliac breadth was measured in the CT scan images using the 3D ruler tool in Amira software. The final sample consisted of 209 individuals, 60 females and 149 males.

To assess bone strength, we analyzed diaphyseal cross-sectional geometry in the tibia (Ruff, 2019). Cross-sectional geometric analyses of limb bone diaphyses are based on modeling the bone as an engineering beam and calculating properties that reflect strength of the beam under loading (Ruff, 2019). In this study, we focused our analyses on properties that characterize strength of the tibial diaphysis in relation to the three types of loading it normally experiences during routine activities like walking and running: bending, axial compression, and torsion (Burr et al., 1996; Yang et al., 2014). These properties included cortical bone area, which describes diaphyseal resistance to axial loading, and polar moment of area, which describes diaphyseal resistance to torsion and average bending.

Geometric properties were measured in the mid-diaphysis of the tibia, defined as half the bone's articular length (Ruff, 2019). For each person, their full-body CT image stack was imported into Amira software and their skeleton was segmented from surrounding soft tissues. A tibia was then cropped out and saved as a separate CT image stack. Next, the tibial CT image stack was imported into ImageJ software and the bone was aligned longitudinally using the BoneJ plugin (Doube et al., 2010). Finally, on the aligned tibia, the transverse CT image slice corresponding to the mid-diaphysis was selected and geometric properties were calculated using BoneJ. In BoneJ, bone was distinguished from non-bone in CT images using the half-maximum height thresholding method (Doube et al., 2010).

Statistical analyses were conducted in JMP software. To test the first hypothesis, we used a general linear model (GLM) to test the association between body weight and tibial strength properties (cortical bone area and polar moment of area), controlling for sex, age, stature, and pelvis breadth. To test the second hypothesis, a GLM was used to test the association between waist circumference and tibial strength properties, controlling for sex, age, and body weight. Statistical significance was judged using a 95% criterion ($p \leq 0.05$).

RESULTS

Among individuals in the sample, there was a high prevalence of overweight and obesity. Among women, 33% and 38% of individuals were overweight or obese, respectively. Among men, 37% and 32% of individuals were overweight or obese, respectively.

In the GLM used to test the first hypothesis, sex, stature, and pelvis breadth were all significant predictors of tibial mid-diaphyseal polar moment of area ($p < 0.0001$, $p = 0.0001$, $p = 0.013$, respectively). After controlling for these variables, as well as age, body mass was significantly positively associated with polar moment of area ($p < 0.0001$) (**Figure 1**). Sex and stature were also significant predictors of cortical bone area ($p < 0.0001$ and $p = 0.0003$, respectively). After controlling for these variables, as well as pelvis breadth and age, body mass was significantly positively associated with cortical bone area ($p < 0.0001$) (**Figure 2**).

In the GLM used to test the second hypothesis, sex and body weight were also significant predictors of tibial mid-diaphyseal polar moment of area ($p < 0.0001$ for both variables). After controlling for these variables, as well as age, waist circumference was not significantly associated with cortical bone area ($p = 0.72$) (**Figure 3**). Sex, age, and body weight were all significant predictors of cortical bone area ($p < 0.0001$, $p = 0.030$, $p < 0.0001$, respectively). After controlling for these variables, waist circumference was not significantly associated with cortical bone area ($p = 0.94$) (**Figure 4**).

DISCUSSION

We know that malnutrition causes the human body to prioritize reproductive health. The human body will impair brain function and burn fat, muscle, and even resorb bone in some situations. Studies on athletes with low energy availability demonstrate how having low energy availability and low activity levels can be unhealthy and harmful to the human body (Loucks et al., 2011). It makes sense that the opposite of this trend would be true, and the lack of support for the second hypothesis may not completely discount this line of thinking. The question this paper seeks to address is how surplus energy availability affects bone growth. Is it possible that both factors (energy availability and load magnitude) effect bone growth in developing humans? The supported hypothesis confirms that the higher mass of the obese individual causes the skeleton to adapt and grow.

The high prevalence of obese or overweight people in the sample illustrates the correlation between bone strength and load magnitude. The data show that bone mass density has a positive relationship with body mass. This supports hypothesis one on grounds that simply having a larger frame over a lifetime will lead to an increase in bone mass. A higher amount of mass exerting its force on the skeleton over a long period of time will cause the skeleton to adapt. Thus, high load magnitude over a long period of time leads to an increase in bone density.

The data do not support the second hypothesis. There is no apparent relationship between waist circumference and cortical bone area. Excess energy availability, at least as it is represented by waist circumference, seems to have little effect on bone growth. The excess energy does not seem to go toward bone growth. It instead goes just to adipose tissue formation or other processes not involving bone growth. The data indicate that increases in bone mass probably come exclusively from loading rather than a combination of both factors. Bone is responsive over a long period of time to a high magnitude of load rather than excess energy availability. Although nutrition and diet also work on this longer timescale, this does not seem to affect bone mass density in the terms of this study.

The second hypothesis can be explained via two processes: human energy metabolism and adipose tissue formation. There is seemingly no correlation within the numbers of the second hypothesis because excess calories go towards the formation of adipose tissue. Thus, there is no direct, exact correlation between excess energy availability and bone mass. The “middle-man” between these two characteristics is adipose tissue itself. Excess energy creates adipose tissue, which adds mass to the human frame, which over time, and at a greater magnitude causes bone mass density to rise.

There exists a debate in the literature surrounding the nature of healthy bone vs. unhealthy bone (Hoy et al., 2013, Inayat et al., 2022). While it is generally true that bone strength increases with bone density, it is important to ask how this increase in strength affects humans in their daily lives. A bone that is strong but lacks toughness will break easier than a healthy bone that does not sacrifice one characteristic for another. A bone that is structurally too rigid will break easier than a bone that has balanced characteristics. It is easy to just look at the positive relationship between the two statistics, but it is certainly important to look at the bigger picture in terms of health.

While it is true that exercise increases bone mass (Guadalupe et al., 2009), it is true paradoxically that not exercising also ultimately leads to an increase in bone mass. Both the lack of exercise and the presence of it increases bone mass density. These processes both lead to an increase in mechanical load on the skeleton, and, as the human body usually does, the skeleton must adapt to this increased load magnitude. While exercise and the lack of it cause an increase in bone mass, exercise is healthy, and being sedentary is not. Certainly, it is healthier to have an active lifestyle and healthily gain bone mass rather than unhealthy bone mass from an increase in heavy adipose tissue.

CONCLUSION

A holistic view of the results of this study suggests that bone strength does increase in response to a higher magnitude of load over time, and that there is seemingly no direct correlation between excess energy availability and increased bone strength. The explanation for the second hypothesis being not supported rests in adipose tissue creation being the "middle-man" between excess energy availability and an increase in bone strength. Consuming excess energy leads to weight gain, which puts more stress on bones, causing them to grow stronger to adapt.

An interesting direction to take further study could be to look at evolutionary reasons and compare humans to other primates and other animals at that to see if this is true morphologically across the organismal board. This phenomenon is more prevalent in organisms that experience greater evolutionary pressures from their environment than humans. It makes sense, then, that these same pressures affect humans still even though we have eliminated many of the pressures of natural selection. Perhaps the second hypothesis that waist circumference and tibial strength is true in non-human animals. If this were true, it could be explained through human advancements in technology eliminating many of the pressures of natural selection. In the wild, it could present some post-reproductive benefit for animals to gain bone mass as they gain weight in their old age.

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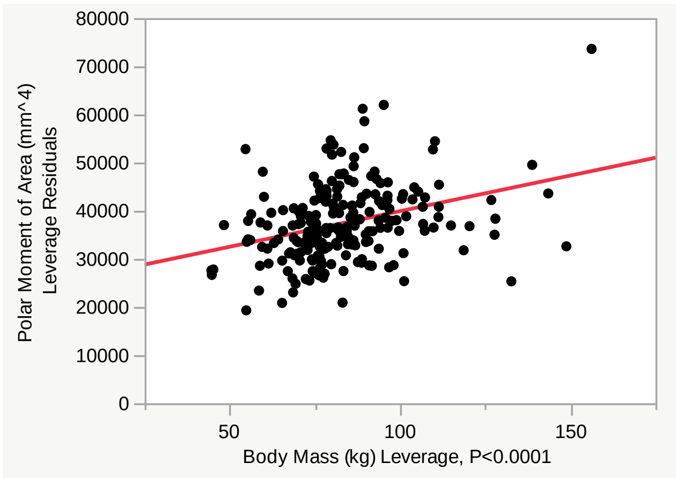

Figure 1. *General linear model fixed effect leverage plot.* Positive association between polar moment of area and body mass (p < 0.0001) when accounting for sex, stature, pelvis breadth, and age. Shaded area depicts confidence curves, visually depicting whether the test is significant at the 5% level.

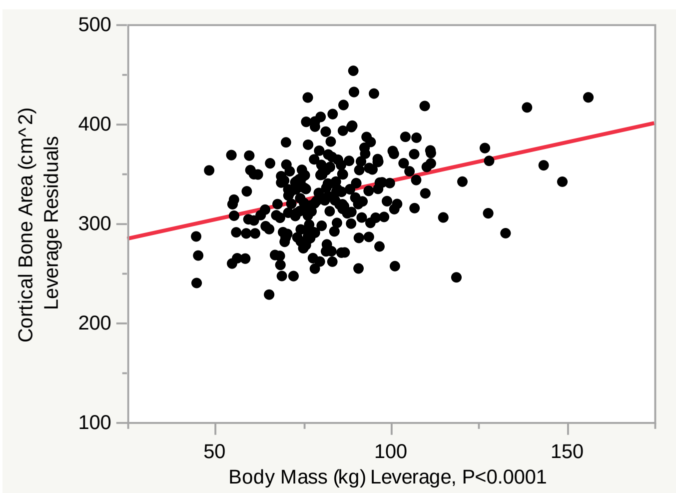

Figure 2. *General linear model fixed effect leverage plot.* Positive association between cortical bone area and body mass (p < 0.0001) when accounting for sex, stature, pelvis breadth, and age. Shaded area depicts confidence curves, visually depicting whether the test is significant at the 5% level.

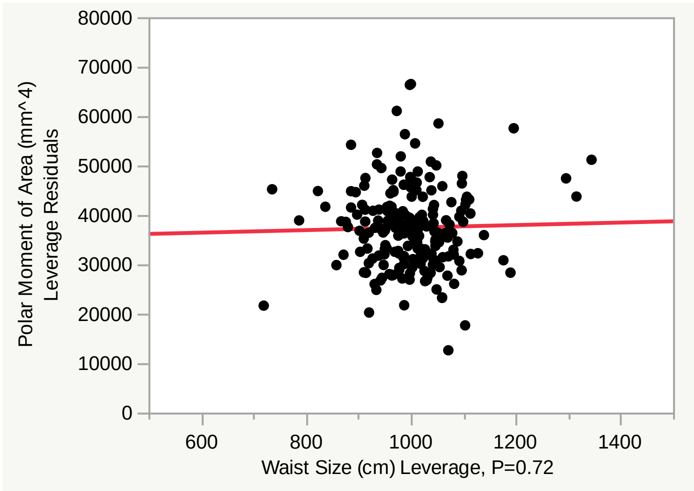

Figure 3. *General linear model fixed effect leverage plot.* No association between polar moment of area and waist size (p = 0.72) when accounting for sex, age, and body weight. Shaded area depicts confidence curves, visually depicting whether the test is significant at the 5% level.

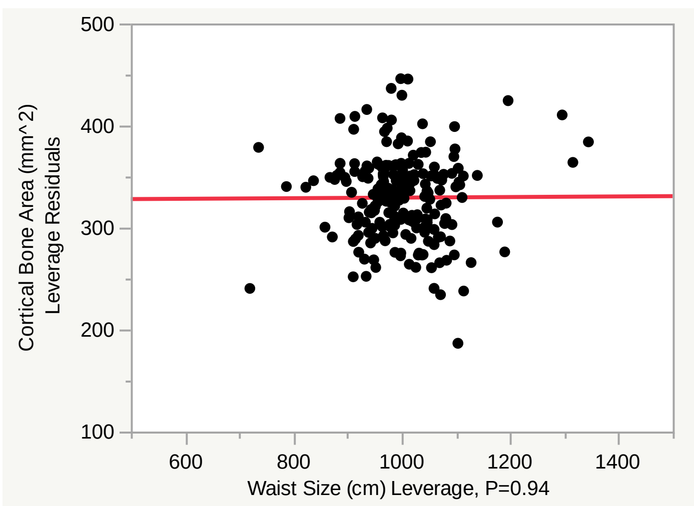

Figure 4. *General linear model fixed effect leverage plot.* No association between cortical bone area and waist size (p = 0.94) when accounting for sex, age, and body weight. Shaded area depicts confidence curves, visually depicting whether the test is significant at the 5% level.