



Estrogen and Bone-Muscle Strength and Mass Relationships

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The largest voluntary loads on bones come from muscles: To adapt bone strength and mass to them, special strain threshold ranges determine where modeling adds and strengthens bone, and where remodeling conserves or removes it, just as different thermostat settings control the heating and cooling systems in a house- If estrogen lowers the remodeling threshold, two things should occur. First, at puberty in girls, bone mass should begin to increase more than in boys with similar muscle strengths, owing to reduced remodeling-dependent bone losses, while gains from longitudinal bone growth and bone modeling continue normally. That increase in bone mass in girls should plateau when their muscle strength stops increasing, since their stronger bones could then reduce bone strains enough to turn modeling off, but could let remodeling keep conserving existing bone. Second, decreased estrogen secretion [or a related factor(s)], as during menopause, should raise the remodeling threshold and make remodeling begin removing that extra bone. That removal should also tend to plateau after the remaining and weaker bone lets bone strains rise to the higher threshold. Postmenopausal bone loss shows the second effects. Previously unremarked relationships in the data of a 1995 Argentine study showed the first effects. This supports the idea that estrogen can affect human bone strength and mass by lowering the remodeling threshold, and loss of estrogen would raise the threshold and help cause postmenopausal bone loss even if other factors help to do it. The Argentine study also suggested ways to study those things and the roles of muscle strength and other factors in controlling bone strength and mass in children and adult humans. Those factors include, in part, hormones, vitamins, calcium, diet, sex, race, age, medications, cytokines, genetic errors, gene expression patterns, and disease, (Bone 22:1-6; 1998) © 1998 by Elsevier Science Inc. All rights reserved.

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Between muscle and bone there can be no change in the one but it is correlated with changes in the other. . . . (D'Arcy Thompson, 1917)

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Introduction

In most women, accelerated loss of bone next to marrow (spongiosa and endocortical bone) begins at menopause and continues until 75%-85% of the premenopausal bone mass remains. Then further losses usually fall to and plateau at age-normal lower rates ("mass" has its meaning in absorptiometry here).³⁹ Efforts to explain that took two main tracks.

Biochemical and cell-biologic explanations focused on osteoclasts and/or osteoblasts and their responses to things such as parathyroid hormone, calcium, and estrogen. One idea suggested that loss of osteoclast depression by estrogen causes postmenopausal bone loss.^{1,33} Another idea suggested that loss of an estrogen effect on osteoblasts reduces their activity relative to osteoclastic activity to increase bone losses and cause osteopenia (less bone than normal).^{20,31,36,40} If so, and other things being equal, the hormone could help keep an existing bone mass, but would not increase it: Decreased hormone secretion should increase bone losses on all bone envelopes (periosteal, Haversian, endocortical, and trabecular surfaces), and as long as the decreased secretion continued the losses should not fall to and plateau at lower rates.¹²

A newer explanation depends on bone-modeling drifts, remodeling basic multicellular units (BMUs), their thresholds, and their responses to mechanical influences. It suggests that estrogen [or a related factor(s)] could lower the bone strain threshold that helps remodeling to control conservation and removal of bone.^{4,9,14,28} If so, and other things staying equal, (1) Increased estrogen secretion at puberty should make girls add more bone than before in relation to the mechanical loads on their bones, but later, that gain should tend to plateau even though estrogen secretion continues. (2) Decreased hormonal levels during menopause would increase bone loss, which later on should tend to plateau, too, even though estrogen levels remained low.

Postmenopausal bone loss clearly reveals the latter effects. Relationships noted in data from an Argentine study reveal the former effects, too.⁴⁷ Summarized below, that study also suggested safe and noninvasive ways to study how varied factors affect the modeling and remodeling, thresholds and their effects on bone strength and mass in growing and adult humans. Explaining how the Argentine data support the newer explanation depends on some physiology. Summarized next.

Pertinent Bone Physiology

Neoplasms, infection, and longitudinal bone growth excepted global bone modeling by drifts provides the chief mechanism for increasing our bone strength and mass, while global BMU-based remodeling provides the chief mechanism for removing mechanically unneeded bone.^{4,10,11,15,22,25,32} No evidence known to us

shows that modeling reduces bone strength and mass or that remodeling increases them ("global" means averaged over whole bones or skeletons)

Where bone strains frequently exceed a modeling threshold range that may center near 000 microstrain modeling begins to increase bone strength and mass. Where strains stay below that threshold, mechanically controlled modeling stops increasing bone strength and mass.^{5,10,12,15,23-30,45} For comparison, bone fractures at ~25000 microstrain.³² Modeling becomes relatively ineffective in cortical bone in adults, but it can apparently affect trabeculae throughout life.

Where bone strains stay in or below a lower remodeling threshold range, as in disuse, BMU creations increase on all bone envelopes, while in bone next to marrow completed BMUs make less bone than before. Yet, BMUs keep resorbing and making nearly equal amounts of bone on the Haversian envelope, since permanent Haversian porosity does not increase, excepting a quite small age-related increase, and transient remodeling space effects.^{32,38} This "disuse-mode" remodeling begins to cause permanent losses of bone only where it touches marrow. This reduces bone strength and mass and can cause osteopenia. Where strains exceed this threshold, resorption and formation in completed BMUs next to marrow begin to equalize. This conservation mode of remodeling begins to conserve existing bone mass, which tends to prevent osteopenia or progression of an existing one.^{11,17} This little-studied remodeling threshold range may center near 50 - 100 microstrain.

The difference between the amount of bone resorbed and made by the typical completed BMU has been signified by p. When that resorption and formation are equal, p=0 (i.e., no difference in their amounts), as on the Haversian envelope and in conservation-mode remodeling. When BMUs make less bone than they resorb, p is negative (less formation than resorption), as in bone next to marrow and in disuse-mode remodeling. It seems BMU creations and p need not always respond in the same sense to some agents. For example, when bone microdamage increases, BMU creations can increase on all bone envelopes to repair it,³⁴ and p tends toward zero on those envelopes. Yet, during acute disuse, BMU creations can increase on all envelopes and p still tends toward zero on the Haversian envelope, but it goes markedly negative where bone touches marrow.¹² This should explain why the resulting bone loss comes from bone next to marrow. In effect, p would determine if and where remodeling conserves or removes bone, while BMU creations would affect only the rates of remodeling-dependent bone turnover and net losses.

The modeling and remodeling thresholds can determine where bone strength and mass do or do not satisfy the mechanical demands on them, and where existing bone is or is not needed for mechanical reasons. In principle, many factors could change the set points of those thresholds. The end of the Abstract listed some examples. This article concerns possible effects of estrogen [or a related factor(s)] on the remodeling threshold.

Those arrangements normally make modeling and remodeling adapt a bone's strength and mass to the largest strains caused by voluntary physical activities^{10,11}. Trauma excepted, muscles cause the largest strains, since muscle forces on bones must overcome two resistances to move us around during work and play. Body weight provides the first resistance. The poor lever arms most muscles work against provide the second and larger resistance.^{6,32,35,43} As a result, it takes more than 2 kg of muscle force on bones to move each kilogram of body weight around on earth.^{6,32,43}

This means whole-bone strength should correlate better with muscle strength than with age or body weight alone, an old idea⁴⁴ that recent studies support.^{41,42} Bone modeling and remodeling

have other functions and determinants that are not discussed here.

In children, bone strength and mass increase chiefly because longitudinal bone growth and modeling add bone faster than remodeling removes it.² In adults, modeling nearly ceases but remodeling does not, which helps to cause a slow, age-related expansion of marrow cavities, thinning of bone cortices, and net losses of spongiosa. It should follow that if conservation-mode remodeling became more efficient during growth, continued longitudinal bone growth and bone modeling would increase bone mass more rapidly than before.

Bone's materials properties change little with age, species, and sex,^{8,18,32} so increased bone strength usually accompanies increased bone mass, too. In healthy subjects, that means bone mass can provide useful indices of whole-bone strength as well as of the amount of bone tissue in whole bones.^{8,18,32}

Predictions

If estrogen [or a related factor(s)] lowers the remodeling threshold, the above physiology would predict five effects. (1) In girls near puberty, bone strength and mass should begin increasing faster than before, since the previous remodeling-dependent bone losses would decrease while modeling-dependent additions of bone would continue normally. (2) At the same time, bone mass should begin increasing faster than in boys with similar muscle strengths (not with similar body weights or ages). (3) In girls, that increase in bone mass should plateau when muscle strength stops increasing, even though estrogen secretion continues, because then their strengthened bones could reduce strains to the modeling threshold and turn modeling off, but still leave conservation-mode remodeling on. (4) Reduced estrogen secretion at some later time should raise the remodeling threshold and make disuse-mode remodeling remove that extra bone and cause osteopenia. (5) That loss should also tend to plateau after the remaining weaker bone lets strains rise to the higher remodeling threshold and turns conservation-mode remodeling back on, even though reduced estrogen secretion continues.⁹

A summary follows of data that could test the previously untested first three of those five predictions.

The 1995 Argentine Study

Zanchetta et al.⁴⁷ used dual-energy X-ray absorptiometry (DXA) to estimate, among other things, total body bone mineral content (TBMC) and lean body mass (LBM) in 778 healthy Argentine Caucasian children (345 boys and 443 girls) between 2 and 20 years of age. The children were not selected by economic status. To ensure normal values, the study excluded children with weight or height more than 2 standard deviations different from the norm, as well as children receiving medications known to affect bone physiology and children with a bone age more than year different from the chronological age. The data were tabulated as means of 1-year age groups, so children in any -year age group were more than 6 months older than the previous age group and <6 months younger than the next one. The children were studied in random order with respect to age and sex. A Norland XR-26 HS densitometer with dynamic filtration made the measurements after calibration each day against inert phantoms. For the measurements considered below, the repeatability as the coefficient of variation = S%-2.0%.

The TBMC values in Table I provide an index of the total amount of bone in the skeleton, and thus of bone strength. The lean body mass values in Table 2 provide an index of the total amount of muscle in the body, and thus of muscle strength. For those girls and boys, Figure 1 plots the grams of bone mass on

Table 1. Whole-body bone mineral content (g)

| Age | Males | | | Females | | |
|-------|----------------|------|-----|----------------|------|-----|
| | n | WBMC | SD | n | WBMC | SD |
| 2 | 6 | 431 | 42 | 5 | 344 | 80 |
| 3 | 10 | 494 | 49 | 13 | 446 | 79 |
| 4 | 16 | 527 | 82 | 15 | 505 | 92 |
| 5 | 15 | 665 | 77 | 17 | 671 | 30 |
| 6 | 17 | 724 | 35 | 21 | 717 | 25 |
| 7 | 25 | 856 | 96 | 22 | 813 | 108 |
| 8 | 24 | 1024 | 167 | 33 | 878 | 171 |
| 9 | 26 | 1023 | 162 | 37 | 1049 | 210 |
| 10 | 37 | 1186 | 225 | 49 | 1196 | 284 |
| 11 | 23 | 1334 | 219 | 34 | 1257 | 274 |
| 12 | 24 | 1438 | 251 | 29 | 1533 | 393 |
| 13 | 28 | 1779 | 312 | 35 | 1964 | 430 |
| 14 | 24 | 2094 | 340 | 23 | 2238 | 313 |
| 15 | 22 | 2364 | 323 | 31 | 2228 | 385 |
| 16 | 17 | 2625 | 309 | 16 | 2397 | 288 |
| 17 | 12 | 2825 | 309 | 26 | 2397 | 283 |
| 18-20 | 19 | 2964 | 345 | 19 | 2368 | 349 |
| | $\Sigma = 345$ | | | $\Sigma = 433$ | | |

Age is given in years \pm 6 months. n = number of subjects in each 1-year age group; Σ = sum of the n's for the whole study; WBMC = whole-body bone mineral content in grams for the 1-year age groups; SD = 1 standard deviation in grams for 1-year age groups. Data were taken from Table 2 in Zanchetta et al.,⁴⁷ with values rounded off to two to four significant figures.

the vertical axis that correspond to the grams of lean body mass on the horizontal axis. Each of its data points provides the mean of all boys or girls in the same 1-year age group. It does not compare bone mass to age or whole-body weights.

Figure 1 shows that at 11-12 years of age, the bone mass index began increasing faster in girls than before. It also increased faster than in boys with the same muscle mass indices. By 14-15 years of age, the muscle index plateaued in girls, as shown by the closely grouped data points for their 15-20-year-

Table 2. Lean body mass (g)

| Age | Males | | Females | | | |
|-------|----------------|--------|---------|----------------|--------|------|
| | LBM | SD | n | LBM | SD | |
| 2 | 6 | 10,510 | 1200 | 5 | 8730 | 6370 |
| 3 | 10 | 13,380 | 720 | 13 | 11,530 | 1490 |
| 4 | 16 | 13,960 | 1600 | 15 | 12,300 | 1560 |
| 5 | 15 | 15,710 | 1490 | 17 | 15,610 | 3900 |
| 6 | 17 | 18,140 | 1470 | 21 | 16,210 | 2050 |
| 7 | 25 | 20,160 | 1980 | 22 | 17,620 | 2210 |
| 8 | 24 | 21,630 | 2230 | 33 | 18,650 | 2150 |
| 9 | 26 | 22,920 | 2570 | 37 | 20,930 | 3110 |
| 10 | 37 | 25,530 | 2190 | 49 | 21,810 | 3330 |
| 11 | 23 | 26,060 | 3220 | 34 | 23,930 | 3840 |
| 12 | 24 | 30,490 | 3950 | 29 | 27,510 | 3410 |
| 13 | 28 | 35,540 | 4920 | 35 | 28,860 | 3630 |
| 14 | 24 | 40,780 | 5810 | 23 | 31,710 | 3350 |
| 15 | 22 | 46,960 | 5340 | 31 | 31,620 | 4530 |
| 16 | 17 | 49,300 | 4350 | 16 | 30,220 | 3680 |
| 17 | 12 | 51,760 | 5530 | 26 | 31,540 | 3850 |
| 18-20 | 19 | 53,470 | 3600 | 19 | 31,630 | 5400 |
| | $\Sigma = 345$ | | | $\Sigma = 433$ | | |

Age is given in years \pm 6 months. n = number of subjects in each 1-year age group; LBM = mean lean body mass in grams for the 1-year age groups; SD = 1 standard deviation in grams for the 1-year age groups; Σ = sum of the n's in the whole study. Data were copied from Table 6 in Zanchetta et al.,⁴⁷ but converted from kilograms to grams

old groups on the far right of the curve. Their bone mass index also plateaued then, and at a higher level than for boys with the same muscle mass index. Since the muscle and bone indices were still increasing in boys at the study's limit at 20 years of age, most 20-year-old men ended up with more muscle and bone than most 20-year-old women.

Comments

Summary

This may be the first comparison of human whole-body bone mass to an index of whole-body muscle strength in the above age span; past studies usually compared whole-body bone mass to age or whole-body weights. When interpreted in the context of the physiology summarized earlier, the present comparison reveals some provocative information. While the usual postmenopausal bone loss shows the predicted initial bone loss and later plateau, Figure 1 reveals the estrogen-associated gain in bone mass at puberty, its association with growing lean body mass, the difference in this respect between girls and boys with similar lean body masses, and the later plateaus in bone and muscle mass in girls, all of which were predicted earlier.

Given qualifications in the next subsection, those observations lend support to six things: (1) Each prediction given earlier; (2) the idea that muscle strength has a major influence on postnatal bone strength and mass; (3) the idea that some non-mechanical agents including estrogen can modify the modeling and/or remodeling thresholds to affect bone strength and mass; (4) a classification of osteopenias and osteoporoses that depends on their biomechanical pathogenesis¹⁷; (5) the paradigm of skeletal physiology from which those ideas come^{12,14-16,25,26}; and (6) proposals in the sections below.

Why did comparisons of bone mass to age or whole-body weights fail to reveal the above effects? Consider that lean body mass forms a smaller fraction of whole-body weight in girls than in boys, and the difference increases after puberty. The lean body mass fractions of these Argentine children, of 76% in girls and 80% in boys at 8 years of age, changed to 63% and 79%, respectively, by age 14, and to 57% and 76%, respectively, by 18-20 years of age (calculated from body weights in Table 1 of the Argentine report⁴⁷; data not shown here; and in Table 2 of this article). Accordingly, if muscle strength influences bone strength and mass more than age or body weight, comparing age and/or whole-body weights to bone mass could minimize or conceal the lean body mass influence on bone mass. This may have happened in past comparisons of bone mass to male-female ages and whole-body weights.³⁹ It did happen in graphs in the Argentine report⁴⁷ that compare bone mass to age in the girls and boys.

Further Studies, and With Better Indices?

We realize the above findings would need confirmation by other studies, partly because of methodological and analytical uncertainties in using total bone mineral content and lean body mass as bone and muscle strength indices, and partly owing to the potential importance of those findings, which support ideas some authorities could view as controversial. Besides other sampling strategies and later DXA equipment and software, other indices could help in doing such studies. As examples, muscle strength can be measured easily in humans to eliminate the uncertainties of lean body mass estimates.^{7,27,41} In particular bones and with suitable software, peripheral quantitative computed tomography (pQCT) can provide reliable bone strength indices (BSIs) that account for both the mass and architectural contributions to bone

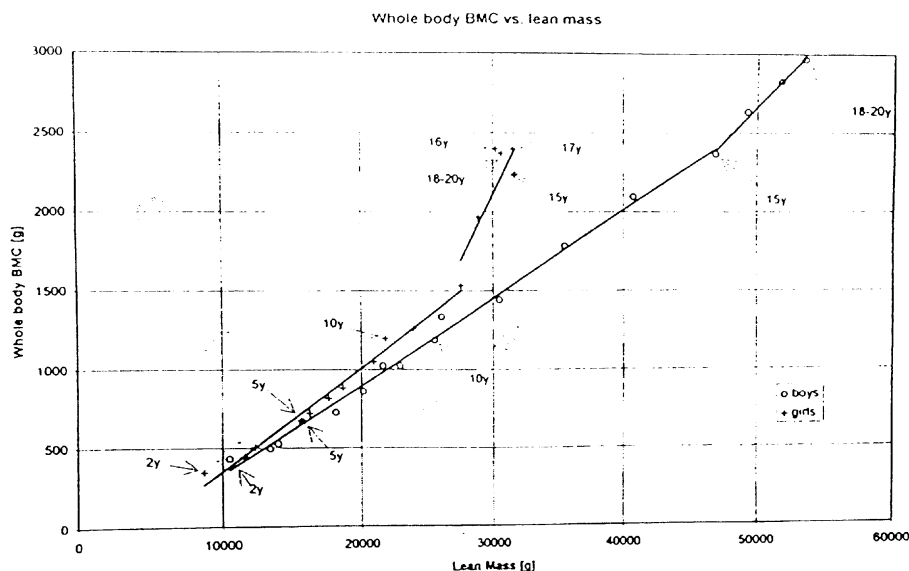


Figure 1. From data in Tables 1 and 2, this figure plots the grams of bone mineral content (TBMC) on the vertical axis that correspond to the grams of lean body mass (LBM) on the horizontal axis. Crosses: girls; open circles: boys. The text assumes the TBMC provides an approximate but useful index of bone strength, and the LBM provides an approximate but useful index of muscle strength. Going from left to right, each data point on each curve stands for an age 1 year older than the data point to its left, and it shows the mean bone and muscle indices for all subjects in that 1-year age group ("n" in the tables). This figure's two curves plot the findings in 345 boys and 443 girls. For similar lean body masses (the muscle index), around 11-12 years of age bone mass begins to increase faster in girls than in boys. By 14-15 years of age, bone and lean body mass both plateaued in girls, as shown by the closely grouped data points for their 15-20-year age groups on the far right side of their curve. Yet, both indices were still increasing in the 20-year-old males. In the figure and tables, the 18-20-year age groups combine as a single data point for girls, and another for boys. The data points for girls aged 14 and 15 years overlap.

strength.^{8,19,41,42} Ferretti⁸ found that they correlated better with fracture strength in long bones ($r > 0.94$, $p < 0.0001$) than bone mineral content alone ($r \approx 0.7$, $p < 0.0001$).

What Problems Might Studies Such as the One Illustrated in Figure 1 Address?

Besides questions about methodology, such studies could help to evaluate physiologic questions that are not easily studied by other means in humans. A few such questions follow.

Would ovariectomy, orchiectomy, and other hypogonadal situations affect the above thresholds and bone-muscle relationships? And other hormones? And some diseases? And different sports, diets, calcium intakes, vitamins, and cytokines? Do they differ in some osteoporoses, as suggested recently?¹⁷ Do they differ in blacks or other races? Do some medications affect them? Do they exist in mice, rats, dogs, sheep, and primates? Do the modeling and remodeling thresholds not change at puberty in boys? Which skeletal compartment(s) stores the extra bone in girls (see the next subsection)? Would supplemental estrogen have similar bone effects in growing and/or adult males? Does the increased horizontal spacing between the data points for boys between 10 and 15 years of age partly reflect an androgen-induced acceleration of growing muscle strength after male puberty, an acceleration that increases bone mass, too?² What happens to these relationships after 20 years of age? Does estrogen affect muscle strength?

Some Speculation About Estrogen Effects on the Modeling and Remodeling Thresholds

The following ideas are offered simply for discussion, following invitations to do so. Any blame for these "trial balloons" should

be directed at the second author (HMF). First we offer some observations, then some assumptions to explain them.

Observations. (1) At menopause, BMU creations increase on all bone envelopes. When women going through menopause take estrogen, BMU creations decrease on all envelopes. (2) When estrogen deficiency begins, ρ tends toward zero on the Haversian envelope, but next to marrow it goes very negative. This increases bone loss, but only next to marrow. Restoring estrogen changes ρ back toward zero next to marrow, which minimizes further losses of that bone.^{20,37} (3) For biomechanical reasons, lowering the modeling threshold should increase periosteal formation drifts, which should increase the outside diameters of long bones. So far, we know of no evidence that estrogen has this effect.

The assumptions. (1) Estrogen lowers the remodeling threshold for BMU creations on all envelopes. (2) Separately, it affects something in marrow that secondarily makes loss of estrogen make ρ go more negative in BMUs next to marrow (as an aside, estrogen increases bone formation in the marrow cavity in birds and mice, and only there). (3) Estrogen does not affect the modeling threshold, contrary to the former idea that it might.⁹

Right or wrong, those assumptions could explain the above observations, as well as the evidence in Figure 1. If girls at menarche do store extra bone next to marrow instead of—or as well as?—on periosteal surfaces, DXA or pQCT studies should show it.

A Possible Reason for Estrogen's Bone Effects?

Could estrogen make growing females add more bone than their physical activities need, to store extra calcium for later lacta-

tion¹³. By the time of birth, a mother's placental circulation supplies a relatively small amount of calcium to the fetal skeleton, but her milk must provide many times that amount between birth and weaning to let her infant's rapidly growing bones mineralize properly.⁴⁶ Given the calcium content of most diets in premodern times, the calcium provided during lactation should come from both her diet and her bone.

If so, when menopause makes pregnancy impossible, that extra bone would become unnecessary. Reduced estrogen secretion would raise the remodeling threshold and make disuse-mode remodeling begin removing the extra bone. That removal should cease when strains of the remaining weaker bone increased enough to make conservation-mode remodeling begin conserving it.

That explanation views postmenopausal bone loss per se as physiology, not a disease. In support of it, bones exist mainly to carry voluntary loads without breaking spontaneously or causing pain, and few postmenopausal women have such problems. Instead, falls due to impaired balance usually cause any fractures they have.^{17,19} Of course, their postmenopausal osteopenia does make falls more likely than before to cause fractures, usually of extremity bones.

Conclusion

Eight decades after D'Arcy Thompson penned the words that opened this article, we just begin to perceive their merit and implications and the biologic mechanisms, processes, and relationships that make them true.

Acknowledgments: The bone and muscle mass relationships recorded in tables in the article by Zanchetta et al.⁴⁷ were perceived by Hans Schiessl, who brought them to the attention of Dr. Frost and Dr. Jee. Those relationships seemed important enough to justify writing an article to describe and discuss them, so Dr. Frost and Dr. Jee wrote this one. However, they both believe Hr. Schiessl deserves the credit for perceiving those relationships, which otherwise could have gone unnoticed for years. Doctor Frost and Dr. Jee had not perceived them, but could help to explain them. Accordingly, they list him as first author of this article, and themselves as second and third authors.

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