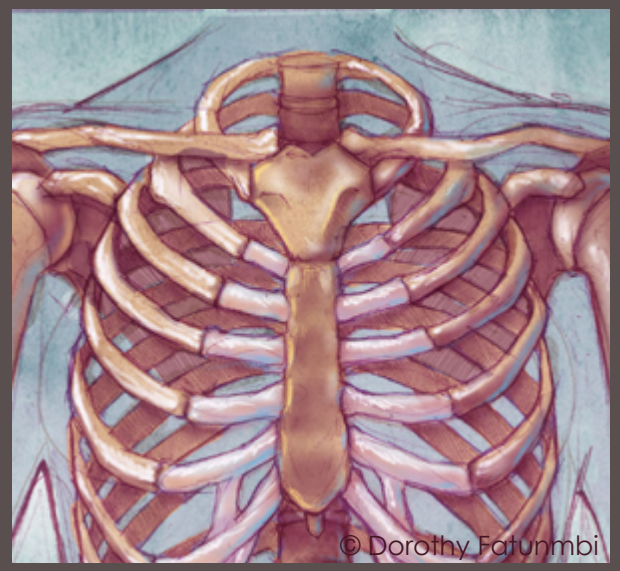
Bone Health in Perspective

A case-based, continuing education resource for healthcare professionals



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The Objective of this Educational Resource

Your goal is to learn the connection between weight-bearing exercise and an osteogenic response in bone.

A Case: Rosa Torres

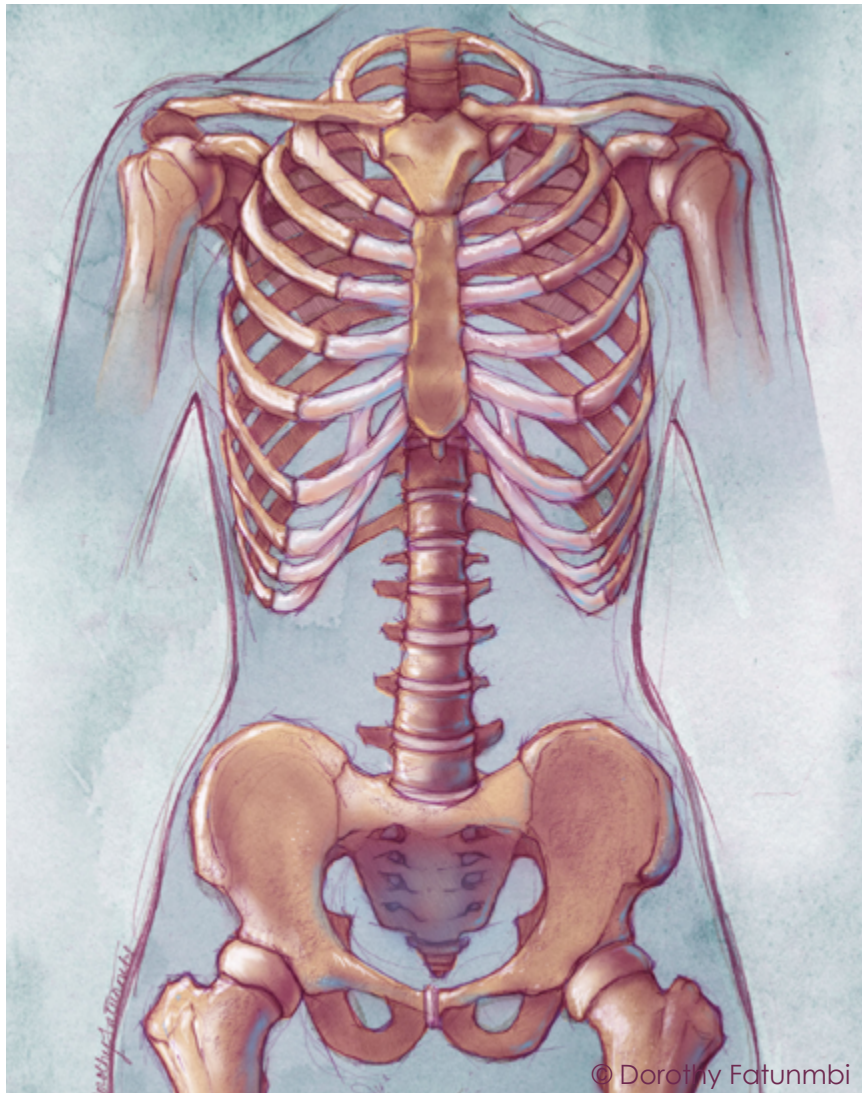
You walk into your patient's room to find Rosa, a 55 year old Hispanic woman with a history of minor fractures. Her DEXA[1] scan results show a BMD[2] T-score[1] of -2.5[3]. This indicates that she has osteoporosis[4]. You recommend exercise, among other things, to Rosa. You place an emphasis on weight-bearing exercise such as jogging or lifting weights.

Rosa is flustered by her diagnosis and she responds,

"Well, I know that bones get weaker with age but I did a little sports in high school. That should have helped me build strong bones. I don't enjoy working out and it's hard to find time. What does exercise do that drinking more milk and taking more vitamins can't do?"

Rosa does not know how weight bearing exercise induces an osteogenic or bone-forming response in bone.

Bone is Both a Tissue and a Structure



From a medical perspective, the skeleton is primarily considered a mineral reservoir. However, it actually exchanges only a small fraction of its mineral content with the rest of the body[5].

Rather, the great mass of mineral found in bone is critical for its mechanical or structural function. **It is from this mechanical function that nearly all of bone's adaptability and responsiveness arises.**

Click here for a list of bone's numerous functions

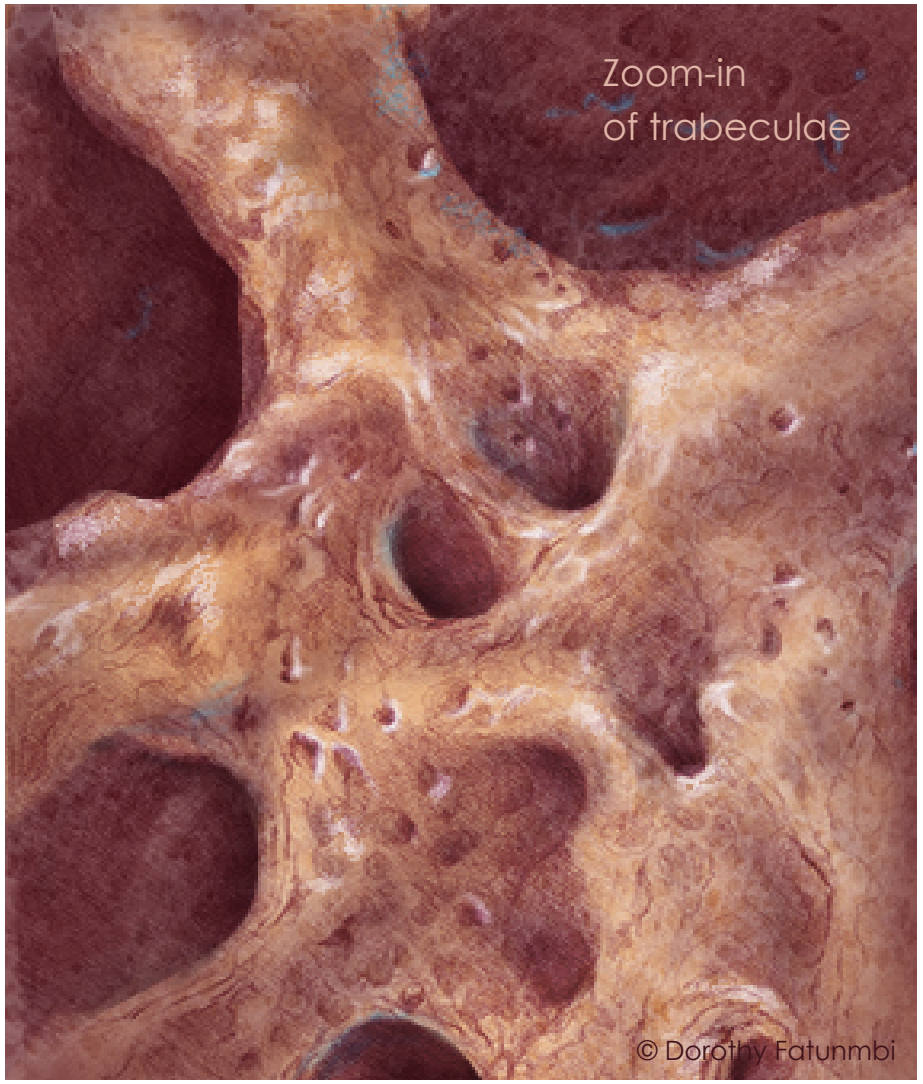
Rosa thinks that *just* increasing her calcium supplementation will be enough to build strong bones. This is a misconception because it only considers bone's metabolic purpose. Considering bone's other functions makes it easier to realize that serving as a mineral reservoir is *not* its primary function.

1. How would you explain to Rosa, why only addressing bone's metabolic function, via supplementation, is insufficient for overall bone health?

Bone's Adaptability After Skeletal Maturity Stems From Remodeling

The coupled actions of osteoblasts and osteoclasts result in the replacement of fatigued or damaged bone.

Bone's Adaptability After Skeletal Maturity Stems From Remodeling



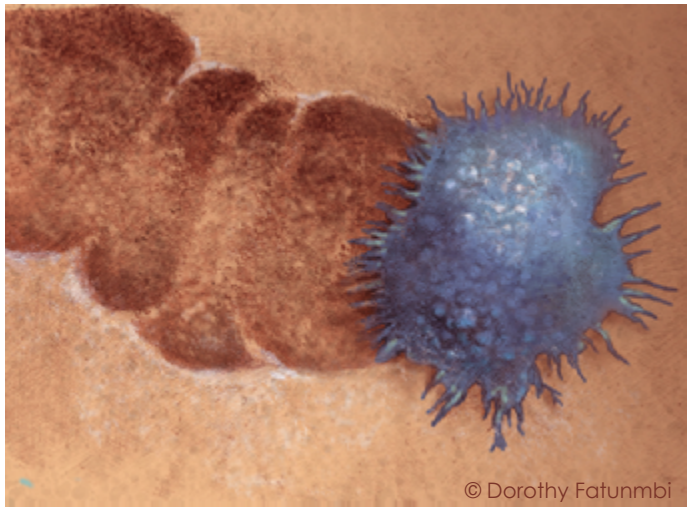
Rosa thinks that the sports that she participated in during high school should have guaranteed her bone strength well into her later years. This is a *partial* misconception.

While physical exercise during adolescence plays an essential role in bone health, it does not guarantee it. **This is because bone is a dynamic, living matrix that *continually* changes throughout life[4].**

After skeletal maturity, bone is no longer actively growing *but* it is still subject to normal fatigue and damage. Continuous remodeling allows the body to replace old, less functional, bone with fresh new bone[6].

2. How would you describe the need for remodeling to Rosa?

An Overview of Bone Remodeling



Osteoclast leaving a trail of dissolved matrix

Osteoblast following behind to fill the hole with osteoid

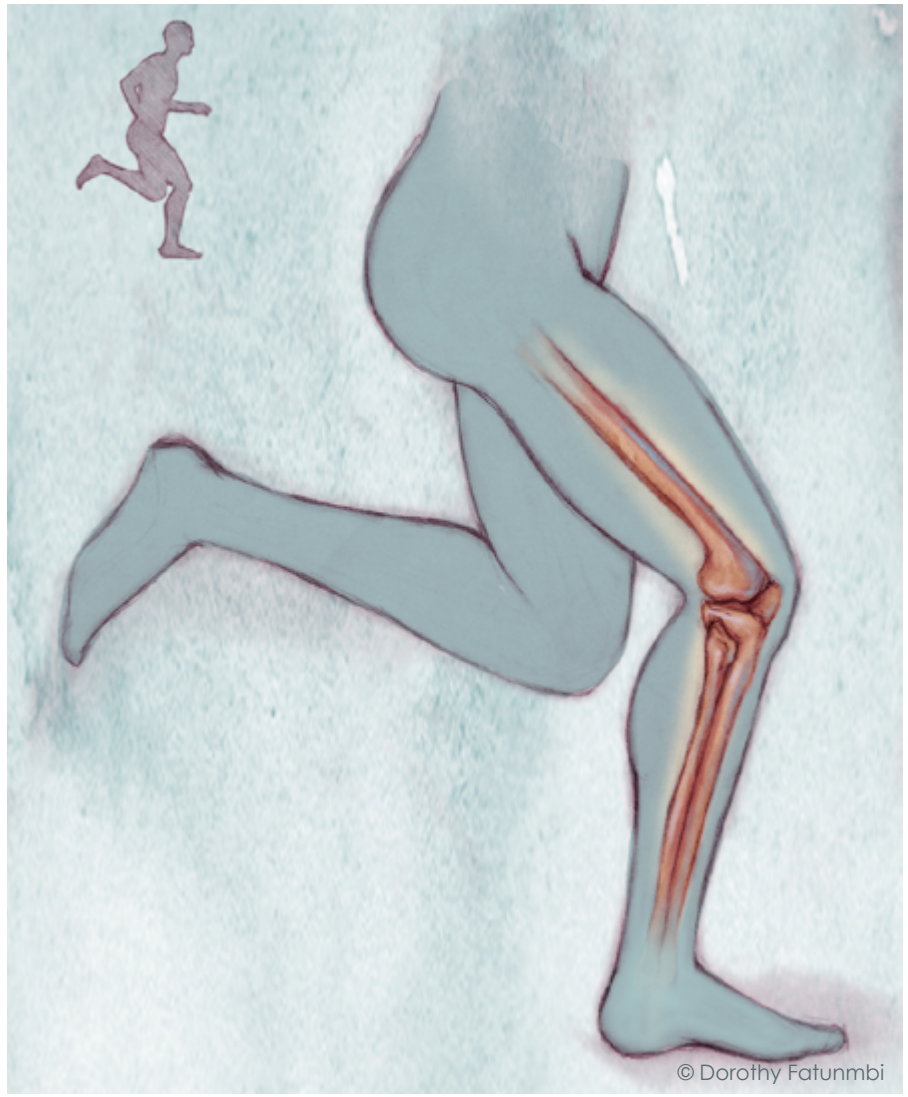
Remodeling is bone's internal response to the external stimuli of mechanical loading upon the skeleton.

It is comprised of activation-resorption and formation phases[6].

- Physical activity stimulates the osteocytes in bone.
- Stimulated osteocytes initiate a signaling cascade that results in the recruitment and activation of osteoclasts.
- Activated osteoclasts attach to the surface of old or damaged bone.
- Osteoclasts (blue) secrete enzymes that dissolve bone's mineral matrix.
- Osteoclasts detach from the newly created cavity and are replaced by osteoblasts. (Formation phase)
- Activated osteoblasts (purple) fill the osteoclast-created cavity with newly synthesized organic matrix called osteoid.
- This matrix will mineralize into new mature bone, strengthening and increasing the integrity of the skeleton.

This process confers immense adaptability to the skeleton. Because it can be stimulated by physical activity, exercise is a modifiable factor that can contribute greatly to overall bone health.

Mechanical Loading Stimulates Bone Remodeling



During physical activity, mechanical forces are exerted on the bones. These include ground reaction forces and the contractile activity of muscles[7].

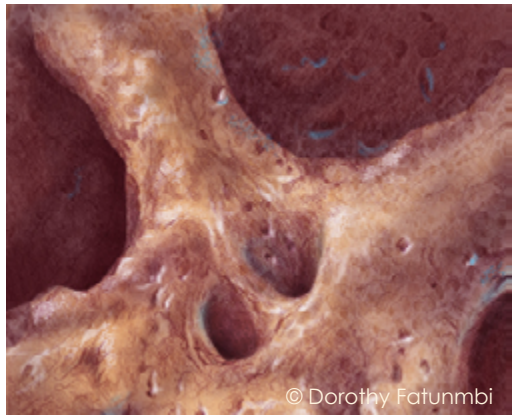
These physical forces drive the adaptation of bone structure. They also result in a maintenance or gain of bone mass. However, not all physical activity loads bone. Swimming and yoga are not considered osteogenic exercises because of their relatively low level of mechanical loading[8].

Rosa says to you, *"I didn't know that my bones were still changing! I thought that they just get built up once and then they naturally get old and weak. OK, since exercise is supposed to help me - I'll join my niece Nathalie when she goes swimming on Wednesdays. Will that help?*

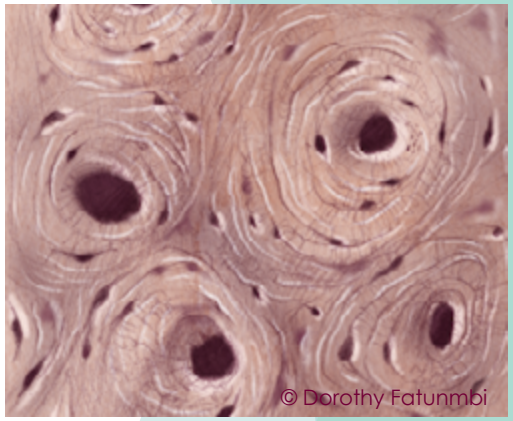
3. How would you explain to Rosa why swimming isn't considered an osteogenic or bone-building exercise?

Anatomy Overview

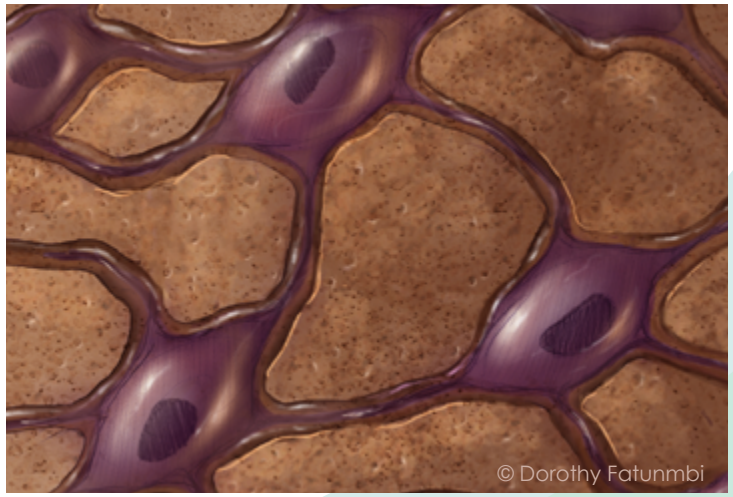
Trabeculae/spongy bone



Zoom-in of trabeculae/ spongy bone

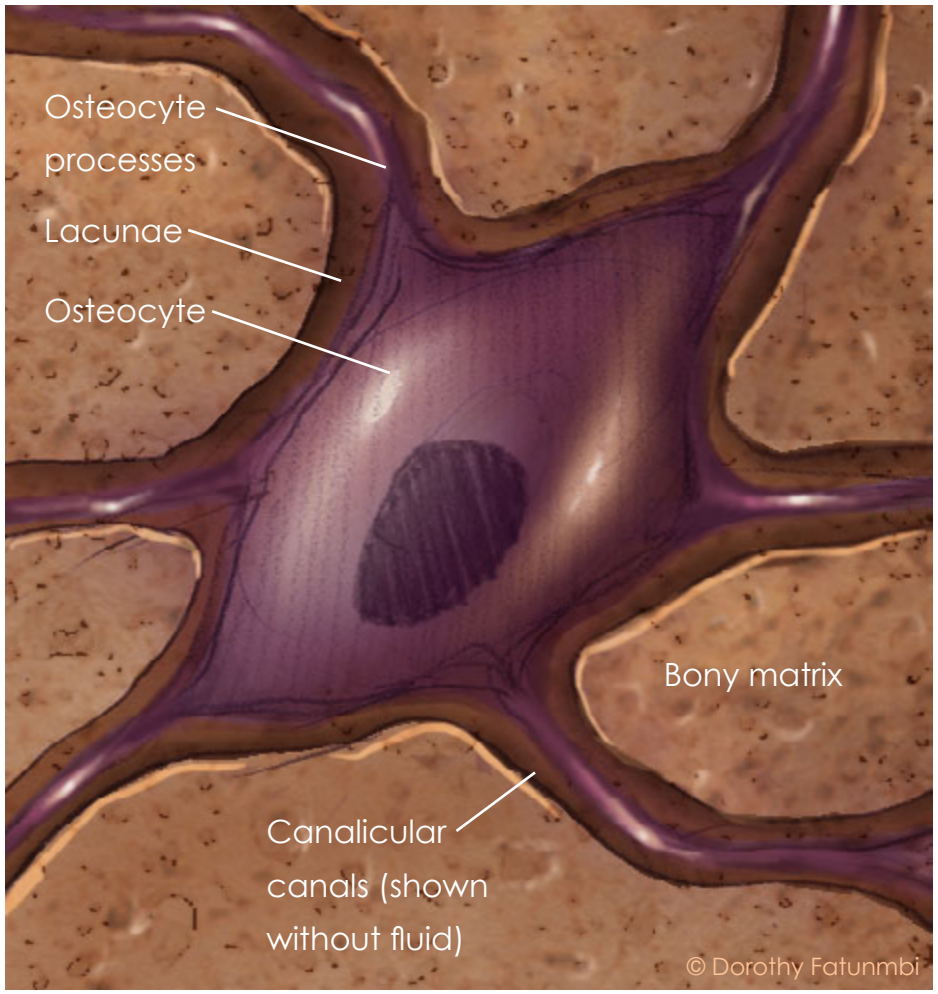


Histology of bone: cross section of trabeculae



Zoom in view of osteocyte syncytium in bony matrix

The Osteocyte's Role in Mechanotransduction



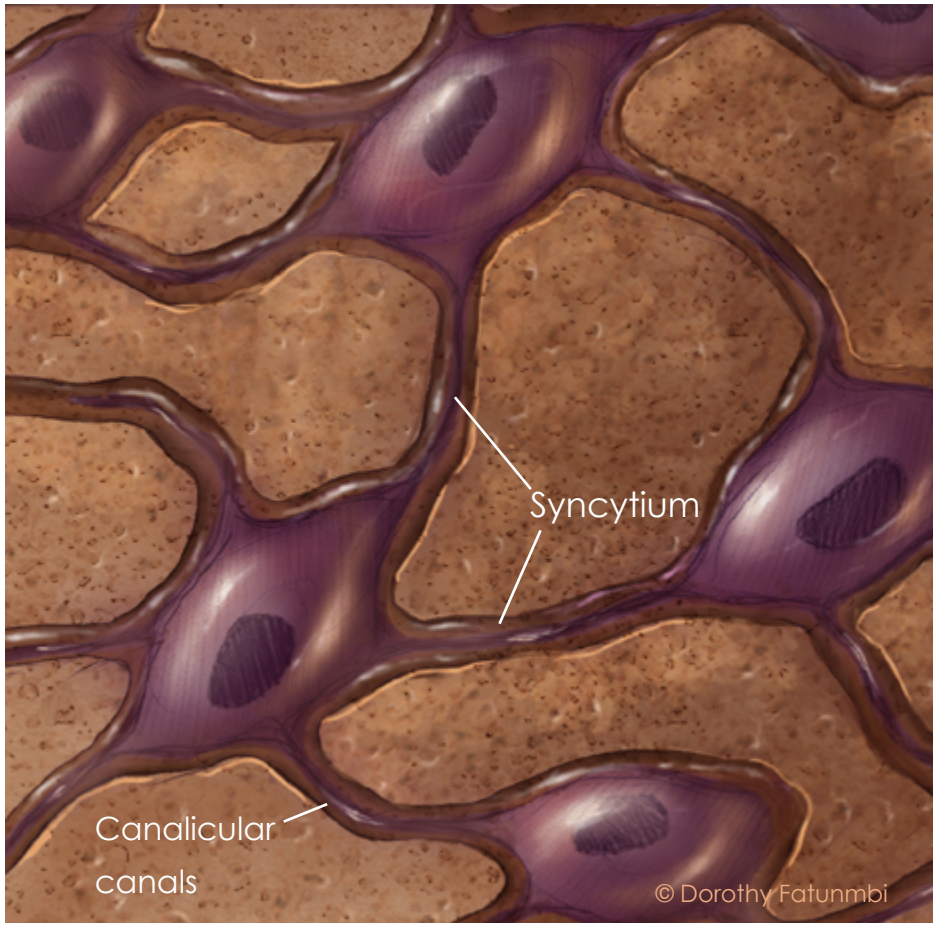
"Well how does my bone know the difference between jogging and swimming? It's not like it has a brain. I still don't understand why I can't just swim. Swimming is a real workout for me. I feel like it has to stimulate my bones enough."

To answer Rosa's question you will need more information.

Bone's adaptive response is regulated by the ability of resident bone cells to perceive and translate mechanical energy into a cascade of structural and biochemical changes within the cells — a process known as mechanotransduction[9].

The next slide will illustrate how osteocytes form a sensory network.

Osteocytes Direct the Mechanical Adaptation of Bone By Sensing Mechanical Loads



Osteocytes are resident bone cells thought to function as sensors of the strain[7] that arises in bone when it is subjected to a mechanical load.

These bone cells have long processes extending from their cell body. These processes form a functional syncytium or communication network with each other via gap junctions[15].

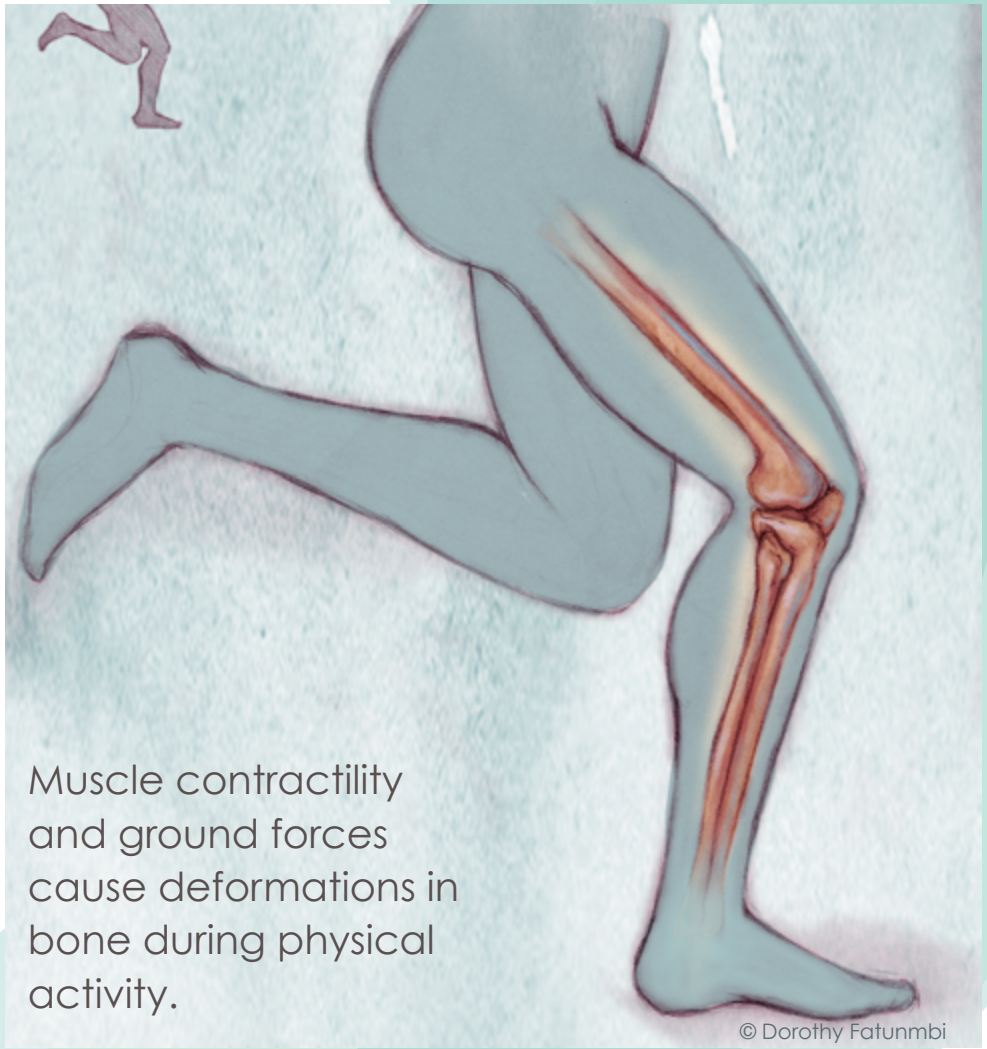
These junctions are between one syncytial process and the next cell body with which they are in contact.

The syncytium is surrounded by fluid inside the canaliculi.

The Osteocyte's Response to Mechanical Forces

How Bone Senses Change[6,7,9,10]

- Mechanical forces are exerted on bone.
- These forces cause strains on the bone and deformation of the bone matrix.

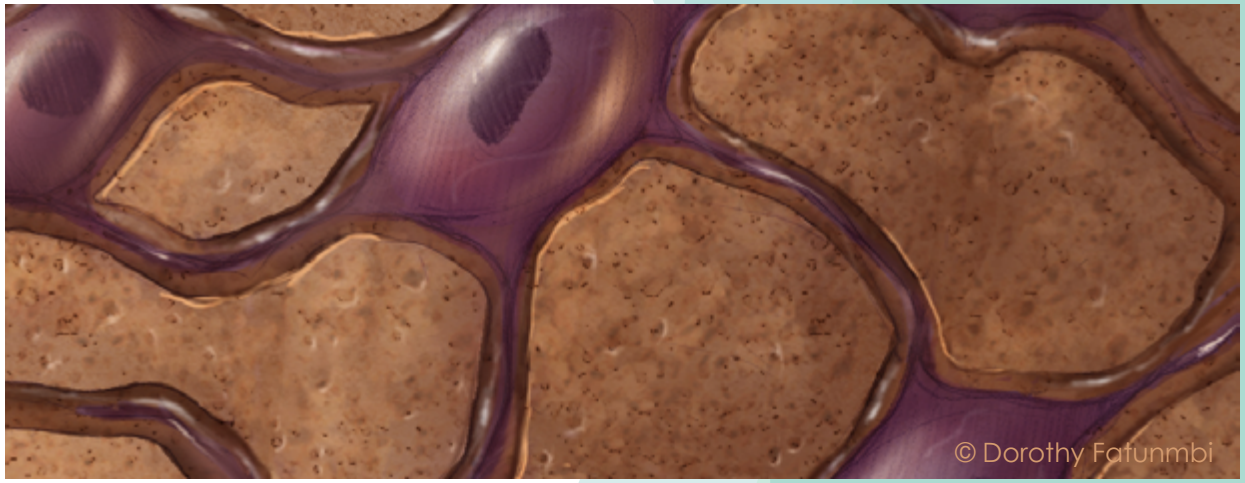


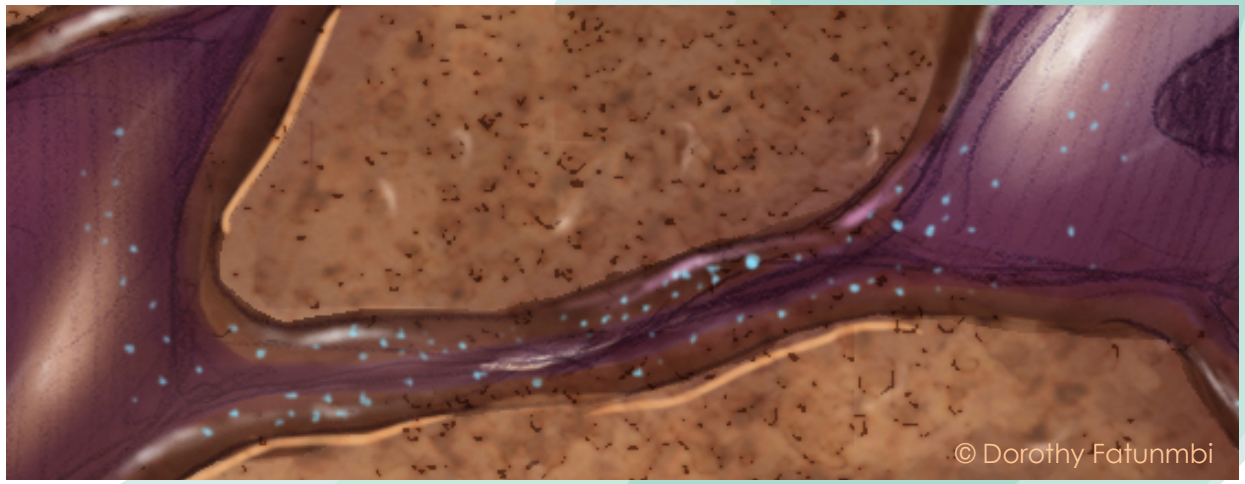
Muscle contractility and ground forces cause deformations in bone during physical activity.

The Osteocyte's Response to Mechanical Forces

How Bone Senses Change[6,7,9,10]

- The deformations drive the movement of interstitial fluid inside the canaliculi.
- The flow of fluid across the osteocyte processes is one type of mechanical signal that is ultimately sensed by osteocyte.
- These now mechanically activated osteocytes produce signaling molecules.



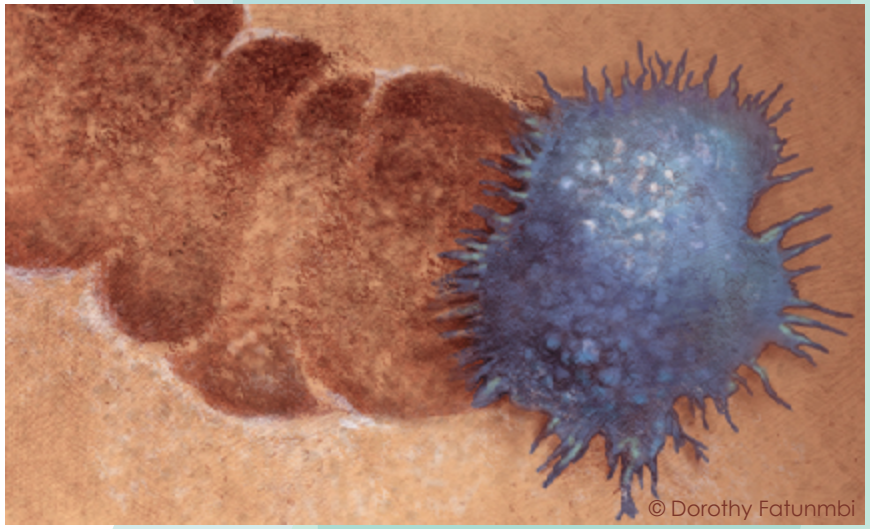


4. How you would explain to Rosa how bone senses mechanical loading?

How Bone Remodels and Repairs Damage

How Bone remodels and repairs damage[6,7,9,10]

- The signaling molecules regulate the recruitment, differentiation and activity of osteoblasts and osteoclasts.

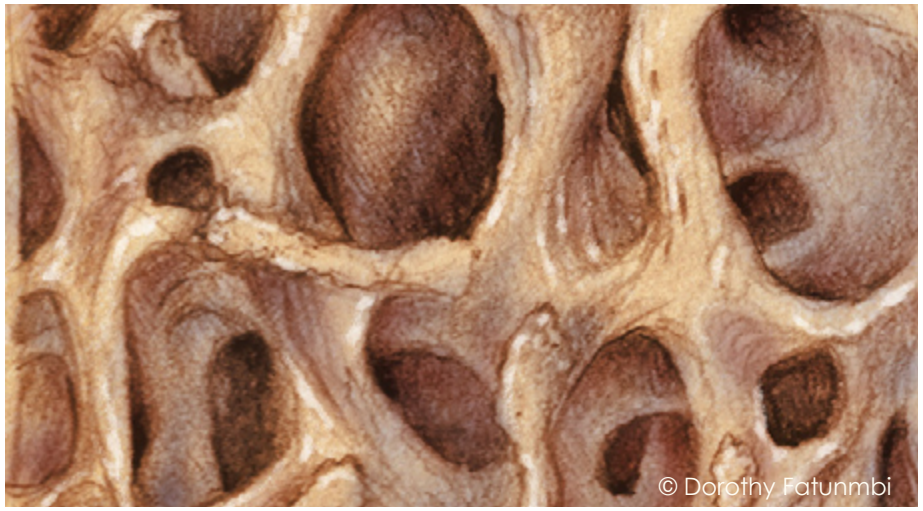


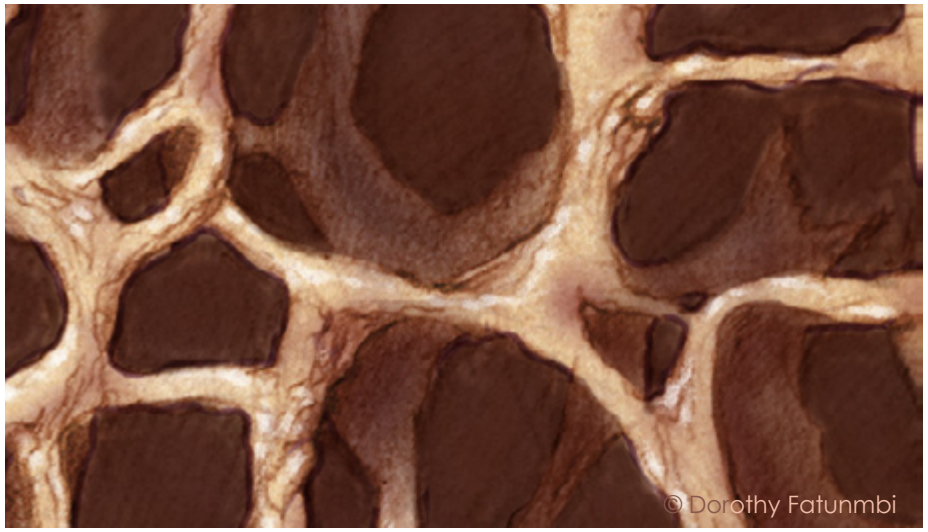
The activated osteoclast (blue) leaves behind a resorption cavity.

Osteoclast leaves. Activated osteoblasts (purple) follow closely behind and fill the cavity with osteoid.

Considering Osteoporosis as a Pediatric Disease With Geriatric Consequences

An Overview of Osteoporosis





Osteoporosis is characterized by reduced bone mass, increased fragility and increased fracture risk[6].

Primary or age-related osteoporosis is the most common disease form resulting largely from age and hormone related decreases in bone quality[4]. Fractures are the most important consequence of poor bone health since they may result in:

- Diminished function[4]
- Loss of independence[4]
- disability[4]
- Premature death[4]

Osteoporosis Is Being Considered As a Pediatric Disease with Geriatric Consequences

Now that Rosa understands that exercise stimulates her bone cells to grow she regrets not exercising earlier. She is also concerned for her 12 year old niece Nathalie. Rosa asks,

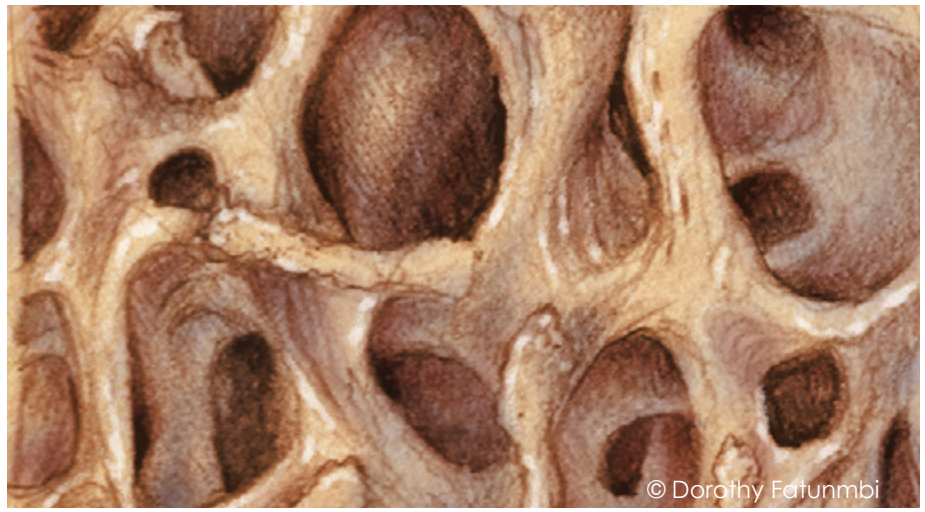
"Now that I have osteoporosis, does that mean my niece Nathalie will have it too? Is this a disease that can I pass on to her? We are very similar and spend a lot of time together"

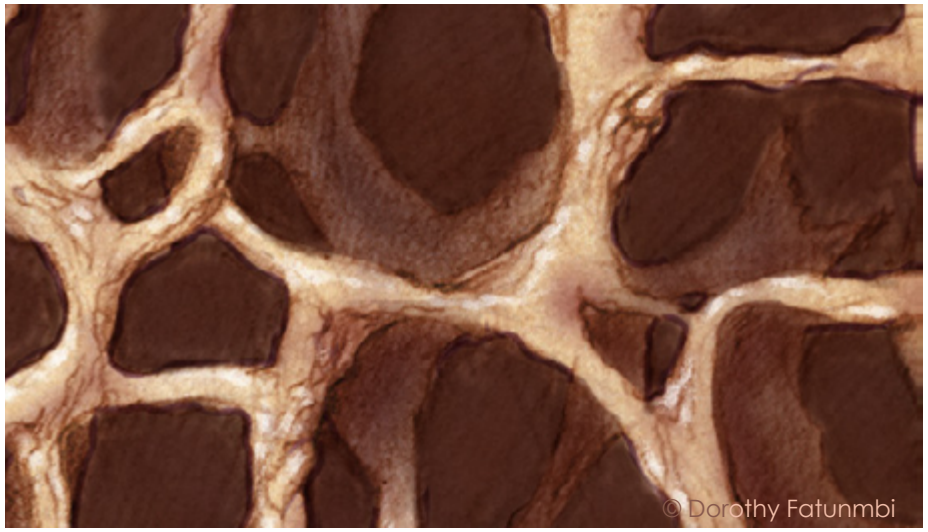
5. After reviewing the text below consider an answer for Rosa.

Primary age-related osteoporosis is the most common form of the disease.

Up to 95% of total bone development is completed before age 18[4]. Any factor adversely impacting bone acquisition during adolescence has the potential to yield long-term detrimental effects.

The Factors That Contribute to Osteoporosis





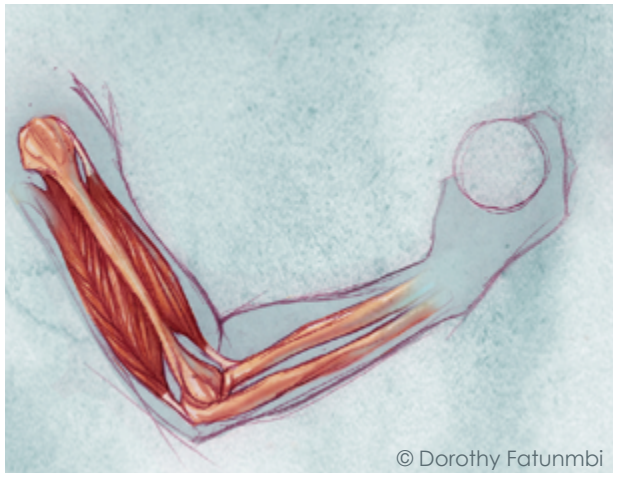
Modifiable factors[4,11,12,13]

- Medications (glucocorticoids)
- Cigarette smoking
- Alcohol abuse
- Low levels of estrogen or testosterone
- Constant dieting
- Low levels of calcium and vitamin D
- Poor nutrition
- Prolonged amenorrhea prior to menopause
- Lack of exercise or overtraining
- Very low body mass

Non-modifiable factors[4,11,12,13]

- Genetics
- Age and Sex
- Ethnicity
- Previous fracture

Osteogenic Exercises Involve Dynamic Loading



Dynamic loading

"OK", says Rosa, "out of that list, exercise is something I struggle with but can modify. What kind of exercises should I be doing since swimming doesn't stimulate my bones enough?"

Dynamic bone loading generates enough force to *enhance* fluid flow while static loading does not. This fluid flow triggers an osteogenic response[7]. Click here for a review.

6. How would you explain dynamic loading exercises versus static loading exercises to Rosa?

Examples of static loading

Activties in which a specific posture or pose is held.

- Pilates
- Yoga
- Isometric exercises
- Swimming

Examples of dynamic loading

High impact, rapid, forceful loading.

- Running, jumping, gymnastics

Changing, diverse or novel loading angles

- Ball sports, gymnastics

Weight bearing, high forces

- Dancing and weight lifting, climbing stairs, jogging, walking, hiking

Changing a Current Mindset about Declining Bone Health

Mindset

Rosa has one last question. She asks you, "***if so many people have this problem or are going to get it, why doesn't everyone learn what you just explained to me?***"

She mentions that she would have exercised more throughout her life if she had known that her bones were always changing and the she could help that process with exercise.

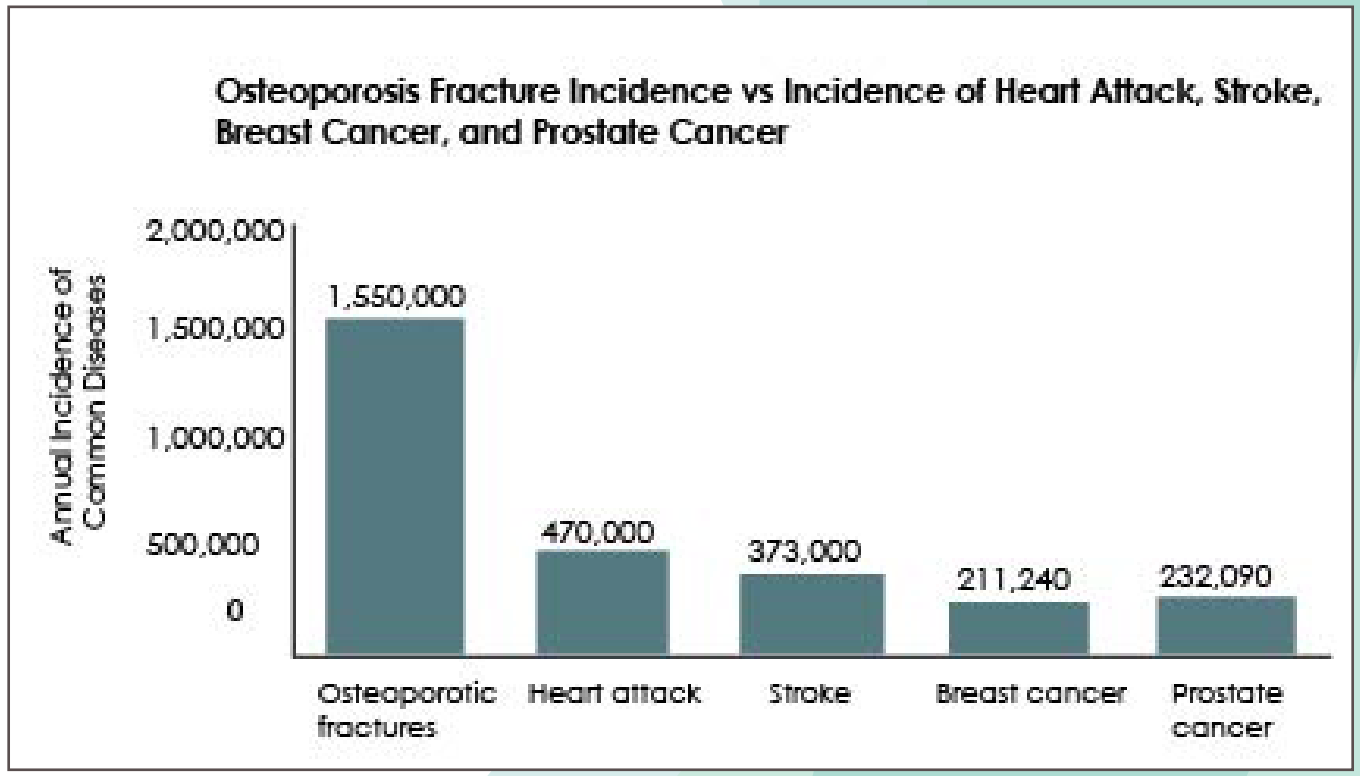
7. Why do you think that more people don't consider osteogenic exercise and its importance in deterring or reversing declining bone health?

The Prevalence and Cost of Osteoporosis

Prevalence
Worldwide, osteoporosis causes more than 8.9 million fractures annually[17].

This means one osteoporotic fracture occurs **every 3 seconds.**

The Surgeon General's Health Report on Bone Health and Osteoporosis estimated that in 2020, one in two Americans over 50 will either have or be at high risk for developing age-related osteoporosis.



(Epidemiology of osteoporosis, 2014)

Changing a Current Mindset about Declining Bone Health

A contribution to the increasing prevalence of osteoporosis is that there are still many doctors who are either unaware or less interested in osteoporosis prevention and treatment because *"they think there is nothing you can do about it*[1]*"*

From the stages of childhood, to adolescence, to adulthood, to midlife and finally later years, bone is undergoing specific changes.

At each stage there is an opportunity to build bone health through proper nutrition and osteogenic exercise.

Increasing the awareness of this among your patients may help to decrease the incidents of hospital visits for the preventable disease of age-related osteoporosis.

Summary and Thank You

This resource was created to convey the modifiability of bone architecture throughout life and to clarify the means by which exercise builds bone and maintains bone health.

Bone health plays an important role in the quality of life of Americans nationwide. Studies indicate that it is declining rapidly despite the large collection of information available about osteoporosis prevention and bone health promotion.

The rising prevalence of osteoporotic fracture may be because of two issues which this study addresses:

1. **A diminished perception** of bone's dynamic nature. It is this very nature that confers levels of modifiability to bone at all stages of life.

2. **Ambiguous connections** between recommended behavioral modifications that promote and maintain bone health and the mechanism by which such actions impart bone health.

Thank you for reviewing this resource. Following, you will find answers and additional resources for your use.

Answers

1. How would you explain to Rosa, why addressing only bone's metabolic function via supplementation is insufficient for overall bone health?

Bone has many functions aside from being a source of calcium. Taking vitamins only gives your bones the ingredients it needs to be strong. But, like when making a recipe, the ingredients have to be mixed and put together to make something. Your bone needs physical activity to take the ingredients that you give it and build strong bones with them.

2. How would you describe the need for remodeling to Rosa?

Your bone is a like your skin in that it's a living organ that responds to things that you do to it. Just like your skin, your bone gets damaged and old over time. The old skin usually falls off to reveal new skin underneath. For your bones, the body uses remodeling to replace old or damaged bone with new, fresh bone throughout your life. Without remodeling, your bones would eventually get so old and build up so much damage over time that they would break.

3. How would you explain to Rosa why swimming isn't considered an osteogenic or bone-building exercise?

Swimming happens in a relatively weightless environment. The bones don't experience as much force during swimming as they would during walking or running. Your bones need a certain amount of impact and force in order to be stimulated to remodel. Swimming does not provide enough impact and force to stimulate remodeling.

Answers

4. How you would explain to Rosa how bone senses mechanical loading?

When you exercise, this applies forces on your bones. Inside your bones are cells called osteocytes. These osteocytes sit inside small fluid filled cavities. The many osteocytes inside your bone are connected to each other like a group of children holding hands. When force is applied on the bone, it places pressure on the fluid that the osteocytes and their interconnected arms are sitting in. This pressure on the osteocyte causes it to send out signals to start bone remodeling.

5. After reviewing the text below consider an answer for Rosa. ("Now that I have osteoporosis, does that mean my niece Nathalie will have it too? Is this a disease that can I pass on to her?")

No, you have age-related osteoporosis. Many factors such as inadequate nutrition, physical inactivity and estrogen decline contribute to cause age-related osteoporosis. None of which you can pass on to your niece. What you can pass on to her are some healthy habits to help prevent her from getting age-related osteoporosis. Since she is young, she can builds up healthy bones now and then maintain them by exercising throughout her life. Life-long bone health can prevent osteoporosis in your niece.

6. How would you explain dynamic loading exercises versus static loading exercises to Rosa?

Dynamic loading is applying forces on the bone in a way that is high impact and quick but not dangerous. Jump roping is an example of dynamic loading. A yoga pose however, is an example of static loading. Static loading is a slow and steady application of force on your bones.

Acknowledgments

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Thank you, to my colleagues in the University of Illinois Biomedical Visualization program for their support as well.

Additional Resource: Bone Health Across the Years

Childhood – Bone Growth

New bone is being added at a faster rate than old bone is being removed. This rapid addition of bone continues until the second decade of life.

Adolescence – Critical Accrual stage

At age nine, an individual's bones undergo a large growth spurt.

By the end of puberty (14-15 years) the adult-sized skeleton is nearly finished at 90% complete.

An individual who fails to achieve optimized bone mass in adolescence will have much less reserve to withstand the normal bone losses that occur later in life (Katherine, 2013). This is a critical time for adequate exercise and nutrition in order to build a large reserve of bone mass.

Adulthood- Maintenance stage

Once optimal bone mass is achieved in late adolescence, maintenance of this bone will contribute gains to overall bone health. During this time, bone formation and resorption are in balance with one another. Continued exercise and proper nutrition will help to maintain the bone mass present.

Additional Resource: Bone Health Across the Years

Midlife- The stage of age-related bone loss

Here, bone loss begins or accelerates for both genders.

The goal in this period is for the individual to keep bone loss to a minimum and avoid threats to bone health.

The relative loss of bone health can be decreased in part by weight bearing exercises and a diet that is fortified with vitamins and minerals that are essential for bone health such as vitamin D and C.

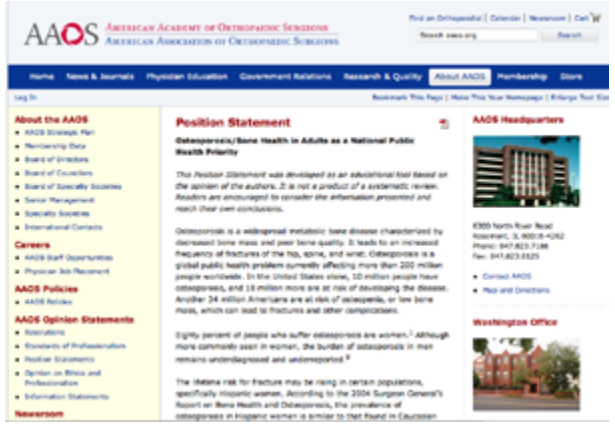
Later Years – The stage of continued bone loss

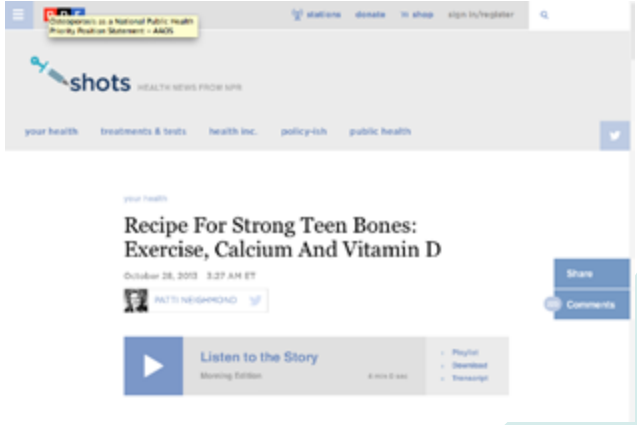
Bone loss continues to occur in both men and women even after age 70.

Despite the continued bone loss that occurs, fractures are not a natural consequence of aging.

Fractures can be prevented to some extent by taking care to controllable factors such as physical activity and diet.

Additional Resources: External links





References

1. Storck, Susan. "Bone Mineral Density Test: MedlinePlus Medical Encyclopedia." U.S National Library of Medicine. Accessed November 29, 2014. http://www.nlm.nih.gov/medlineplus/ency/article/007197.htm.
2. U.S National Library of Medicine. Accessed November 29, 2014. http://www.nlm.nih.gov/cgi/mesh/2011/MB_cgi?mode=&term=Bone Density.
3. "Bone Mass Measurement: What the Numbers Mean." Bone Mass Measurement: What the Numbers Mean. January 1, 2012. Accessed November 29, 2014. http://www.niams.nih.gov/Health_Info/Bone/Bone_Health/bone_mass_measure.asp.
4. U.S. Department of Health and Human Service. (2004). Bone health and osteoporosis: A report of the Surgeon General. (pp. 1-404). Rockville, Md.: U.S. Dept. of Health and Human Services, Public Health Service, Office of the Surgeon General.
5. Martin, R. (2007). The importance of mechanical loading in bone biology and medicine. The Journal of Musculoskeletal and Neuronal Interactions, 7(1), 48-53.
6. Fogelman, I. (2012). Physiology of Bone Formation, Remodeling, and Metabolism. In Radionuclide and hybrid bone imaging (pp. 29-55). Berlin: Springer
7. Klein-Nulend, J., Bacabac, R., & Bakker, A. (201). Mechanical Loading and How It Affects Bone Cells: The Role of the Osteocyte Cytoskeleton in Maintaining Our Skeleton. European Cells and Materials, 24, 278-291.
8. Bachrach, L. (2001). Acquisition of optimal bone mass in childhood and adolescence. Trends in Endocrinology & Metabolism, 12(1), 22-28
9. Tami,A., Netrebko, P., Bauer, T., Knothe Tate, M.L. "The Osteocyte Syncytium in Healthy and Pathologic Human Cortical Bone." Institute of Biomedical Engineering. The Orthopaedic Research Society, Dallas. 2002. Poster presentation

References

10. Berridge, M. (2012). Cellular Processes. In Cell Signaling Biology (pp. 7.79-7.80). London: Portland Press Limited.

11. Schettler, A., & Gustafson, E. (2004). Osteoporosis Prevention Starts in Adolescence. Journal of the American Academy of Nurse Practitioners, 274-282

12. Neighmond, P. (n.d.). Recipe For Strong Teen Bones: Exercise, Calcium And Vitamin D. Retrieved November 21, 2014, from http://m.npr.org/news/Health/240553878

13. Hightower, L. (2000). Osteoporosis: Pediatric Disease with Geriatric Consequences. Orthopaedic Nursing, 19(5), 59-62

14. Goldberg, G. (2004). Nutrition and bone. Women's Health Medicine, 1(1), 25-29.

15. Zernicke, R., Mackay, C., & Lorincz, C. (2006). Mechanisms of bone remodeling during weight-bearing exercise. Applied Physiology, Nutrition, and Metabolism, 31, 655-660.

16. EPIDEMIOLOGY OF OSTEOPOROSIS. (n.d.). Retrieved December 3, 2014, from http://www.medscape.org/viewarticle/517185

17. Facts and Statistics. (n.d). Retrieved August 20, 2015, from http://www.iofbonehealth.org/facts-statistics