Sticks and Stones Need Not Break Your Bones

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1.0 Introduction

When I first started training martial arts at the tender age of seventeen, practice included a demanding and painful regimen of conditioning exercises. One of these exercises involved slamming forearms and shins together with great force. Initially, I experienced a good deal of discomfort because of these exercises, but in time, I became more desensitized to the pain. Some months later while participating in a tournament, something remarkable happened: my opponent attacked with a front kick, and I retreated into front stance while executing a low block to his leg. This low block, executed with no more diligence and effort than during regular practice, resulted in a fractured tibia for my opponent, who was forced to withdraw from competition. I came away from the encounter with only the usual bumps and bruises, and some emotional confusion caused by injuring a colleague during a friendly competition.

Of the many training experiences over the years, including breaking bricks and wood, running barefoot through the snow in near-zero temperatures, and kicking trees, this experience has remained in the forefront of my consiousness as perhaps one of the most remarkable. My reaction to this event is to ask: “Why did my friend’s tibia fracture, while my forearm suffered hardly any damage?” A trained martial artist would likely think of answers that cite correct technical execution of a strong technique along with a particularly potent and concentrated release of energy.

What I intend to explore in this article is neither of these, but instead to focus upon what was happening at the anatomical level. All those painful conditioning exercises did something beneficial to specific parts of my body, something that made it physically hard and capable of repelling injury. What I suspected, that my bones became more dense as a by-product of the conditioning, appears to be substantiated by medical science.

Let us realize that a fully qualified medical study would require a carefully designed and executed experiment - something that I am not qualified to perform. Such a study would test subjects consisting of control groups, who performed no conditioning, and those who did perform the exercises. Then, after some period of time, quantifiable measurements in the form of bone samples would be obtained from the subjects and compared. Obtaining such bone samples requires highly specialized equipment and highly skilled medical training, as well as the usual attention to procedures required when using human subjects as part of a medical study.

Instead of embarking upon a fully qualified clinical study of the effects of specific conditioning exercises upon a few focused points on the human body, I will instead share information obtained from medical literature (anatomy and kinesiology) that describes how our bodies respond to certain types of external forces. Taken in the proper context, this information appears to provide a quantifiable explanation for my early training experience.

2.0 Physical Makeup and Growth of Bones

Bones are not static structures like beams in a building. They are living tissue undergoing continual growth, and they respond to external stimuli. In this section, we examine the makeup of bones and the process of bone growth. In the next section, we examine how growth patterns change in response to external stimuli.

2.1 Constituents and Organization of Bone Tissue

Mature living bone is about 50 percent water and other fluids, and about 50 percent solids. Of the solids, about one-third is organic, and the remaining two-thirds is inorganic. The organic portion of bones can be divided into (1) *cells*, which constitute only a minute fraction of the total weight of bone, (2) *fibrous matrix*, formed largely by fibrils of collagen, a protein substance that can be extracted as glue or gelatin, and (3) amorphous *ground substance* or *tissue fluid*, consisting mostly of complex protein-sugar compounds. The inorganic portion consists of crystalline salts, which are composed primarily of calcium and phosphate.

Bone tissue is sparely permeated with blood vessels, lymph channels and nerve branches. The microscopic *Haversian system* is the structural basis of compact bone. Most conspicuous are the cylindrical tunnels about 0.05 mm in diameter, called the *Haversian canals* or *central canals*, which are usually aligned with the long axis of the bone. They branch irregularly, and contain small blood vessels, lymph vessels, and nerve fibers. Bone tissue is laid down around each Haversian canal in very thin cylindrical, concentric layers known as *lamellae*. Between the lamellae are found many small cavities, called *lacunae*, each of which contains an *osteocyte*, or bone cell.

In particular, it is the collagen fibers and the calcium salts of the matrix that help to strengthen bone. In fact, the collagen fibers of bone have great tensile strength (the strength to endure stretching forces), while the calcium salts, which are similar in physical properties to marble, have great compressional strength (the strength to endure squeezing forces). These combined properties, plus the degree of bondage between the collagen fibers and the crystals, provide a bony structure that has both extreme tensile and compressional strength.

Thus, bones are constructed in exactly the same way that reinforced concrete is constructed. The steel of reinforced concrete provides the tensile strength, while the cement, sand, and rock provide the compressional strength. However, the compressional strength of bone is greater than that of even the best reinforced concrete, and the tensile strength approaches that of reinforced concrete. But, even with their great compressional and tensile strengths, neither bone nor concrete has a very high level of torsional strength (the strength to endure twisting).

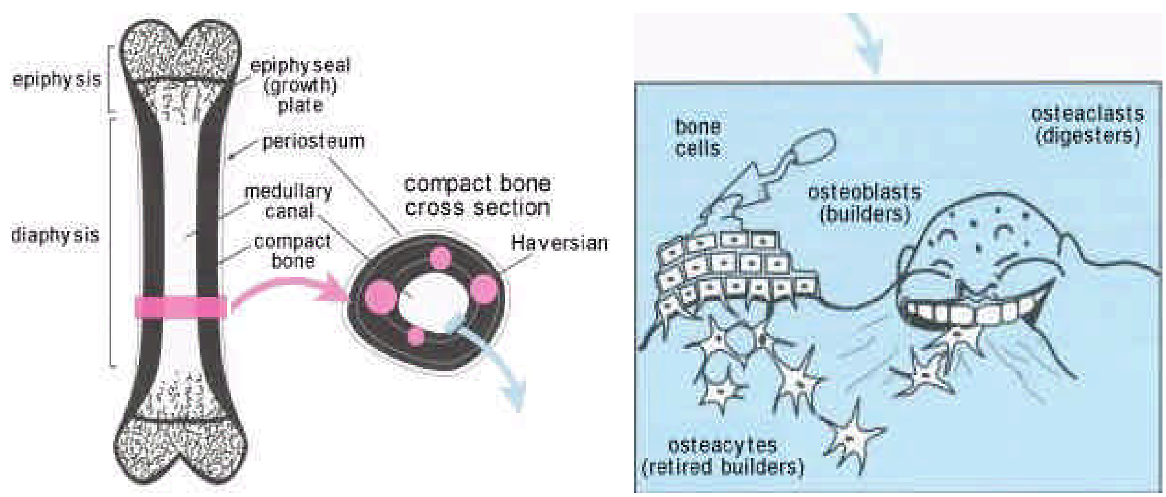
Bones can be classified according to their shapes as: long (including the arm and leg bones), short (including the bones of the wrists and ankles), flat (including the ribs and the bones of the skull), and irregular (including the vertebrae along our spine). In describing the general structure of bone, a long bone will be used as an example (Figure 1). At each end of such a bone there is an expanded portion called an *epiphysis*, which forms a joint with another bone. The epiphyses are composed largely of spongy *cancellous* bone, which provides the greatest amount of elastic strength since the epiphyses are subjected to the greatest forces of compression. The shaft of the bone, which is located between the epiphyses, is called the *diaphysis*. Except for the *articular car-*

tilage that covers the very ends of each epiphysis, the bone is completely enclosed by a tough covering called the *periosteum*.

The periosteum is a connective tissue that covers the outside surface of bones, except at articular surfaces, where it is replaced by articular hyaline cartilage. It has two layers: an outside layer of collagenous fibers, and a deep layer that is osteogenic (that is, capable of producing *osteoblasts*, which in turn may develop into osteocytes). Periosteum is supplied with blood vessels and nerve branches. It is extremely sensitive to injury, and from it originates most of the pain of fractures, bone bruises, and “shin splints.” It adheres to the outer surface of compact bone by sending tiny processes, similar to small roots, into the bone. Muscles are attached to the periosteum, not directly to the bone. The *endosteum* is a similar connective tissue that lines the medullary cavity and Haversian canals, and covers trabeculae of spongy bone. Within the periosteum lies a bony layer called *compact bone*, which is solid, strong, and resistant to bending.

Both the proximal and distal ends typically display protusions that serve as attachment or “pulleys” for tendons and ligaments. The shapes of the articular surfaces are commonly specialized to enable the bone to fit securly into the conformations of its neighbor, and to determine or limit the kind of action possible at the joint. Each articular surface has a cap of hyaline cartilage. This cartilage functions to increase the smoothness of fit, prevent excess wear, absorb shocks, and prevent dislocation of the joints.

FIGURE 1. Bone Tissues



2.2 Bone Growth

In long bones, the growth and elongation continue from birth through adolescence. Elongation is achieved by the activity of two cartilage plates, the epiphyseal plates, located between the shaft (the diaphysis) and the heads (epiphyses) of the bones (Figure 1). These plates expand, forming new cells, and increasing the length of the shaft. In this manner, the length of the shaft increases at both ends, and each head of the bone moves progressively apart. As growth proceeds, the thickness of the epiphyseal plates gradually decreases and this bone lengthening process ends. In humans, different bones stop lengthening at different ages, but ossification is fully complete by about age 25.

In contrast to the lengthening of bone, the thickness and strength of bone must continually be maintained by the body. That is, old bone must be replaced by new bone all the time. This is accomplished as bone is continually deposited by osteoblasts, while at the same time, it is continually being resorbed (broken down and digested by the body) by *osteoclasts* (Figure 1). Osteoblasts are found on the outer surfaces of the bones and in the bone cavities. A small amount of osteoblastic activity occurs continually in all living bones so that at least some new bone is being formed constantly. Except in growing bones, the rates of bone formation (regeneration) and resorption are equal to each other, so that the total bone mass remains constant. The balance between osteoblast and osteoclast activity is maintained until about age 40. After that age, osteosclastic resorption begins to exceed osteoblastic regeneration, and bones decrease in mass and become more brittle.

3.0 Factors Influencing Bone Growth

The structure of bone is well understood, as is the two types of bone growth. Bone elongation, or lengthening, occurs primarily through the first two decades of life. Bone mass density (BMD) growth in bone occurs continuously throughout life through a delicate balance between bone formation and resorption. This section is a survey of historical and current topics about factors that influence changes in bone density.

3.1 Historical Perspective

In the late nineteenth century, a theory was put forth by Julius Wolff, called “Wolff’s Law.” It stated that “every change in the form and function of a bone, or of their function alone, is followed by certain definite changes in their internal architecture, and equally definite secondary alteration in their external conformation, in accordance with mathematical laws.” He believed that the formation of bone results both from the force of muscular tensions and from resultant stresses of maintaining the body in the erect position, and that these forces always intersect at right angles.

In the years that followed, there was much criticism of Wolff’s hypothesis. Some disagreed with Wolff’s dualistic doctrine that bone formation is dependent on both tension and pressure. There was much debate over the years about the relative contribution from muscular tension versus pressure from gravity, and of the relative importance of the role played by muscles and ligaments in reducing, or contributing to stresses in bone tissue. Others disagreed with his mathematical analysis. Wolff’s work is not the earliest to stir controversy. Darwin’s *Origin of Species* attributed the change in bone structure to a change in use. The change in use occured as a result of human evolution from quadrapeds to bipeds. The branch of science that emerged from Darwin and Wolff’s early theories, and controversy, is known as kinesiology - the study of anatomy, physiology and mechanics of body movement.

In a more modern setting, much research has focused on a bone disease known as *osteoporosis*, including cause, prevention and treatment. Osteoporosis is a weakening of bones due to an imbalance between bone regeneration and resorption.

During youth, bone growth is greater than bone loss. At some point as a young adult, the body reaches peak bone mass. After this point, bone loss slowly begins to outpace bone growth. Bones naturally become less dense and weaker with age. Osteoporosis ("porous bone") develops when bones deteriorate to the point where they become fragile and easily fractured. It is most common in post-menopausal women, but may also occur in men and in people who have certain diseases or take particular medications. Studies into the the cause and treatments of osteoperosis serve to provide us with a better understanding of the process of *bone remodeling*.

3.2 Bone Remodeling

Strong, healthy bone is continually maintained through a process known as bone remodeling. Bone remodeling has two phases: resorption and formation. Bone removal is called resorption. The bone-resorbing cells, osteoclasts, remove old bone by releasing acids and enzymes to remove minerals and collagen. Once the osteoclasts have done their job, protein-secreting cells, osteoblasts, deposit new tissue.

Bone remodeling occurs continuously throughout life, although there are certain conditions in which osetoblast activity can be accelerated so as to have the amount of bone formation exceed the amount of bone resorption. One condition that promotes increased amount of bone formation is exercise. Conversely, lack of exercise will tip the balance towards bone resorption.

Mechanical stress is a bone remodeling stimulant. Forces of bone compression stimulate growth of bone density. For example, stress from gravity, as well as from exercise, stimulates bone density growth. Space travelers, for example, have experienced bone density loss in the non-gravity of outer space, and now do isometric exercises during their journeys to partially offset this unfortunate reality ([3],[10)]. Likewise, bedridden individuals experience bone atrophy due to lack of stress on bones.

3.3 Triggering Bone Remodeling

While osteoporosis tends to appear in an older population, studies have shown that children as young as 7-8 years old can significantly increase bone mass through a brief, specific exercise regimen. This may help them "bank" extra bone to prevent osteoporosis when they are much older. The critical component, is "impact loading" exercises that boost bone mass in a targeted area – especially the hips. In the study ([5], [7]), volunteers jumped off two-foot boxes 100 times, three times a week for seven months. The result: they had more than 5 percent higher bone mass than a control group who used the time for stretching and non-impact exercise. The conclusion of this study was that a 5.6 percent increase in bone density in childhood translates into a 30 percent decrease in the risk of a hip fracture in adulthood.

Physical activity has been proposed as one strategy to reduce fractures by increasing bone mass and by preventing falls through improved functional ability. Although the mechanism by which exercise increases bone mass is not clear, it likely influences bone directly through mechanical forces (loading) transferred to bone. One group at Stanford reports development of computer simulations of bone density change in response to a change in physical loading [2]. The existance of these studies indicate that while the osteocytic response to external stimulus may not be well understood, there is a strong correlation between the location of loading and the ability to mathematically predict increase in bone formation.

Bone responds to changes in mechanical loading, and the regulation of bone strength is a function of the loads to which the skeleton is exposed. The most striking examples of this adaptation are reports that demonstrate marked bone loss in the absence of weight-bearing activity, such as occurs in space travel and prolonged bed rest. Conversely, many reports have shown that bone mass among physically active individuals and athletes is significantly higher compared to their nonactive and nonathletic counterparts.

Some studies that have imposed significant mechanical forces via exercise intervention report positive effects on bone mass, although the magnitude of effect is much less impressive than would be predicted from studies on athletes and active individuals [6]. Therefore, the ideal exercise program that maximizes bone response remains elusive. Evidence is accumulating to suggest, however, that exercise that increases muscle strength, mass, and power, may provide the best osteogenic stimulus. Activities of this type provide additional skeletal protection in the older adult by preventing falls, which are highly related to the incidence of fractures, particularly at the hip.

3.4 Mechanics of Remodeling Triggers

Mechanical forces are directly applied to bone by muscular attachments, and individuals with high muscle strength are able to generate large forces during contraction. Thus, muscle strength is a measure of physical fitness that has been studied with respect to skeletal health. Research has shown that the relationship between muscle strength and bone demonstrates site-specificity. Strength of the hip muscles has been related to hip bone mass density (BMD), and grip strength has been associated with forearm BMD. The contribution of muscle strength to BMD in various cross-sectional studies has ranged from 9 to 38 percent in nonathletic adults. Since approximately 60-80 percent of bone mass is estimated to be genetically determined, the relationship between muscle strength and bone is not trivial and again points to the importance of the muscular system with respect to bone health.

Research has demonstrated that male and female athletes who participate in sports that require muscular strength and power (e.g., weight lifting, gymnastics, wrestling) exhibit higher bone mass than those whose sports involve primarily muscular endurance (e.g., distance running, triathlon). Information on the loading characteristics of various activities suggests that walking and slow running provide loads equal to or slightly higher than body weight alone at the spine. In comparison, forces at the spine have been estimated to be five to six times body weight while weight lifting. Jumping associated with gymnastics training may elicit forces as high as 10 to 12 times body weight.

The research on athletes and the size of the load for a specific sport suggests that the skeleton's response to mechanical loading depends on the magnitude of the force. In practical terms, the skeleton must encounter forces that are greater than those it experiences on a day-to-day basis. Even though walking is a weight-bearing activity, its ability to evoke a skeletal response is limited to the older adult who was previously bedridden and unable to ambulate for a period of time. On the other hand, one who performs activities of daily living without assistance will be in a weight-bearing posture much of the day. For this person, walking as an exercise will not exceed the loading threshold of daily activities and therefore will not improve bone mass

The following table lists widely accepted principles that characterize the current understanding of exercise regimens and their effect upon the human skeletal system. .

TABLE 1. Principles of Training Regimens to Increase Bone Mass Density

Specificity	The impact of the training should be at the bone site of interest since loading seems to have a localized effect.
Overload	The training stimulus must include forces much greater than that afforded by habitual activity.
Reversibility	In the absence of the training stimulus, the positive effect on bone will be lost.
Initial Values	Individuals with low BMD will have the greatest potential to gain from mechanical loading.
Diminishing	Each individual’s biological ceiling determines extent of adaptation to the training.

4.0 The Arm-Slam Exercise

The “arm-slam” exercise was first taught to me very early in my martial arts career. It can be practiced with a partner, or alone against a stationary object such as a small-diameter tree or a “wooden dummy.” The exercise involves repeatedly impacting the blocking surfaces of the arm against those of your partner, or with a stationary object, if practicing alone.

Figure 2 illustrates solo practice of the arm-slam exercise against a stationary object. The first movement of the exercise is an inside low block, striking with the inside surface of the forearm. The second movement is to execute an outside middle block, striking again with the inside surface of the forearm. The third movement is an outside low block, striking with the outer surface of the forearm. While shown in Figure 2 using a stationary horse stance, the exercise can be used with other stances, and combined with retreating or attacking footwork in order to increase the complexity for advanced students. There is also a variation of this exercise that uses the shins rather than forearms as the striking surface, and it produces similar results in the legs.

The purpose of this exercise is to promote an increase in bone mass density in specific, targeted regions by overloading the bone with force and stress, thus achieving the goal of specificity. The sharp impacts of the exercise produce stress that far exceeds that possible with normal day-to-day activities, thus achieving the goal of overloading.

FIGURE 2. Right Side Arm-Slam Exercise

First, execute an inside low block striking the pole with the inside of the forearm. Next, execute an outside middle block, again striking the pole with the inside of the forearm. Finally, execute an outside low block striking the pole with the outside of the forearm.

5.0 Conclusion

Bones are composed of a combination of organic and inorganic components, formed through a continual process of osteoclastic activity called bone remodeling. Bone growth is characterized using bifurcated categories: bone length and bone density. Lengthening of bones occurs in the first two decades of life in humans. In contrast, bone density growth is carried out through a process called bone remodeling. Bone remodeling is the process of bone regeneration and resorption, and occurs continuously through life. Studies have shown that lack of stress on bone tissue tips the balance more in favor of resorption, resulting in loss of bone mass. Conversely, high-impact exercise tips the balance more in favor of bone regeneration, resulting in increased bone mass density. Increased bone mass density, which results from increased levels of bone regeneration, is strongly correlated with reduced likelihood of fracture induced by external stresses to bones. The mechanism that produces increased levels of regeneration from high-impact exercise is the subject of ongoing research, but is believed to be related to the responsive migration of osteocytic cells into regions of stress in order to repair the microfractures caused by high-impact activities.

Biomedical research has shown that stresses applied to bone have a direct, positive effect in terms of promoting osteoclastic activity, or bone remodeling. Training regimen strategies resulting from research suggest that high-impact activities can be targeted at specific portions of the bone, which will in turn cause that portion of the bone to exhibit elevated levels of remodeling. From these conclusions, this article suggests that individuals that participate in impact-based arm- and leg-conditioning exercises will benefit in bone density levels greater than those who do not participate in such training. Following from increased bone density levels will be the reduced likelihood of bone fracture caused by impact, such as those experienced by a martial artist during regular training.

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