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Original Article

Mechanism of strengthening the skeleton using plyometrics

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Abstract
The relationships between the nature of physical activity and the peculiarity of the formation of the skeleton has beendiscovered by J. Wolff at the end of the XIX century. Wolff`s law can be represented by the simplified thesis: 1) bone (and the whole organism) adapts to a certain type of mechanical load; 2)the shape of the bone depends on its function; 3) if the bone is under load, it is restored; if the bone does not receive it – it dies. Jumping training is widely used to increase strength, speed, power and agility. There is a branch of sports training load, which is based on the shock-jumping method – plyometrics. Plyometric training has a powerful effect on the daily reproduction of the chemical composition of skeletal bones, tendons, and joints. Plyometric training prevents sprains of ligaments and tendons and strengthens joints. The mechanism of bone destruction and formation, the role of cancellous bones in providing $Ca^{2+}$to muscles for their contraction and relaxation are considered. The generalized molecular-cellular mechanism of strengthening and growth of bones under the influence of plyometric training is presented.The generalization of the results of experimental studies presented in scientific publications as well as observations of motor activity and training process suggests that the effect of physical activity on bones is realized through at least three routes: 1) pressure perunit surface of the bone, which causes micro-deformations (compression, tension, and twisting); 2) the movement of bone fluid, which is a typeof massage of the network of osteocytes and osteoblasts; 3) the effect of osmotically active increase in the internal pressure of bone fluid on bone cells in the lacunar canal system.
Key words: sports health; plyometric training

Introduction

A certain type of physical load models and remodels the shape of the bones in animals and humans. In animals of different ecological niches (i.e., flying, ground, earthworks), adaptive anatomical and morphological features, which were developed during physical activity, are fixed. Thus, the scapula in birds is similar to the rib, and in mammals – to the shovel; the chest bone in birds has a powerful keel, which is absent in mammals. The main physical activity during the flight of a bird is associated with lowering of the wing. This type of movement hasformed powerful large and small pectoral muscles, and for their attachment – a massive sternum with a keel. The horizontalposition of the body in animals causes an additional load owing to the retention of a heavy scull. Under the influence of daily physical effort, these animals formed a large muscular mass of the back, a flat shoulder with a keel, and vertebrae with high spinous processes for their attachment. To prevent injuries in some individuals that move by jumping or galloping, there was an increase in the legs and strengthening of the limbs. The digging mole has a "sixth finger" on its front limb and a significantly strengthened shoulder girdle (Kuibida & Anzina, 2016a, 2016b;) The relationships between the nature of physical activity and the peculiarity of the formation of the skeleton has beendiscovered by J. Wolff at the end of the XIX century (Wolff, 1892 as cited in Bergmannet al., 2011). Wolff`s law can be represented by the simplified thesis: 1) bone (and the whole organism) adapts to a certain type of mechanical load; 2) the shape of the bone depends on its function; 3) if the bone is under load, it is restored; if the bone does not receive it – it dies. In the second half of the XX century, H. Frost proposed the theory of mechanostat(Frost,1987). It is based on the idea that a certain type of physical activity (similar to a designer who constructs and sews clothes)models and remodelsnot only the external shape of the bone but also its internal geometry and special structure. The use of jumping load is an important tool of modern theory and methods of maintaining health and sporting achievements (Pivovarniček et al., 2015; Matteo et al., 2015; Muanjai et al., 2015; Şanhin et al., 2015; *Yiannis Michailidis, 2015;* Shakhlina et al., 2016;Ortinau et al., 2017; Troy et al., 2018; Beato et al., 2018;El-Ashker et al., 2019; Silva et al., 2019;Bourzac et al., 2020; Negra et al., 2020;Bouguezzi et al., 2020).

With the progress of civilization, hypodynamics has become an integral part of the modern world. In Ukraine, approximately 3.5 million people have a systemic bone disease – osteoporosis (Povoroznyuket al., 2012). Unfortunately, various effects of physical activity on the mechanostat of bones, condition of joints and tendons, and mechanism of their daily destruction and reproduction have been insufficiently studied. This

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problem is relevant and requires a comprehensive study from the point of view of biological basics of the theory and methods of strengthening the human musculoskeletal system in humans of different age using plyometrics.

Materials and Methods

The literature search performed for this review article is based on the use of the abovementioned keywords (sports health, plyometric training) in electronic databases PubMed and SPORTDiscus. Search terms regarding the effectiveness and specifics of the impact of a high-carbohydrate diet on the human body were introduced in various combinations using bibliographies in original scientific articles and reviews.

Discussion

Human skeleton performs the following main functions: 1) support – it is attached to the striated muscles; 2) Ca^{2+}depot –the spongy parts of the vertebrae, ribs, foot, hand, epiphysis of the femoral, shoulder, elbow, and radial bones accumulate calcium and phosphorusions. The processes of bone regeneration and growth predominate in childhood and adolescence, and degradation – in adulthood. Without thedestruction of an old bone, a new one is not formed. Teeth grow in childhood, and alveoli are formed to fix them owing to the point destruction of the jaws (Ataman, 2018).Modeling and remodeling of bones and cartilage are performed by the following cells: stem cells, osteoblasts, osteocytes, osteoclasts, and fibroblasts. Reproduction begins when stem cells from bone marrow or adipose tissue enter empty bone channels. They undergo division and transform into young bone cells – osteoblasts.Eventually, osteoblasts become mature – osteocytes, age, and cease to exist owing tothe participation of devouring cells – osteoclasts.New stem cells settle in cavities orcanals, and the cycle repeats. It has been determined that complete bone replacement occurs every ten years(Rosen, 2003).The spongy tissues of the vertebrae, head, and areas of the femur and humerus, foot, and hand are most actively renewed. The bone is destroyed by special bone-eating phagocytes –osteoclasts. They secrete destructive ferments: proteases – perform the decomposition of proteins; collagenases –decompose "bone glue" collagen; hyaluronidases – destroy hyaluronic acid; alkaline phosphates – cleave phosphoric acid residues from organic compounds, and acids (i.e., lactic and citric) – decompose inorganic bone substances. The rate of remodeling is defined by the number of osteoclasts and osteoblasts. The number of skeletal bone tissue is determined by the balance between processes of its resorption and recovery. The process of demineralization of the bones and leaching of $Ca^{2+}$is provided by osteoclasts, which are activated by young osteocytes.These data support the assumption that healthy osteocyte is a unique cell. It can increase bone mass and accelerate the removal of minerals from gaps and tubules,which leads to its reduction (O'Brien et al., 2008). The results of a previousstudy (Morris et al., 1997) confirmed the beneficial effects of jumping exercises on strengthening the skeleton. The abovementioned authors extended the assertion that landing when jumping from a low starting block creates themaximum effort, and bone density increases faster than during running. It has been shown that after 10 months of running and jumping on to the starting block the mineral content of the femur increase by 6% (Fuchs et al., 2001). The highest mineral density of bones of inferior limbs occurs at the point of the most powerful shock – in the hip joint during jump landing. The crucial factor for the intensive increase of the bone strength is not theeffort (height of the starting block or bench), but the intensity of the change in applied force and its frequency(Rubin & Lanyon, 1984).The most effective are those movements and physical exercises that dramatically change the movement and pressure of bone fluid. The technique of strengthening the skeleton with the help of jumping exercises is based on the mechanism of bone cell response to fluid moments. To visualize adaptive changes to training jumps or running, we createdour own diagram (Figure1). The abovementioned diagramshows that there is a gap between a living cell (osteocyte) and a hard bone. The space of the split is filled with bone fluid (painted dark in the figure). Through this fluid, living bone cells receive nutrients, O_2, and various regulatory effects and return metabolic products to the blood. During jumps and jump-outs, bone fluid movesup and down in lacunae and canals with osteocyte processes. The stronger, more intense, and shocking is the impact of the fluid in the upper and lower phase of the jump, the greater is the pressure created on the cell. A dramatic change in bone fluid pressure (which is similar to a typeof massage – shaking) activates osteocytes and osteoblasts. Activated cells produce more collagen, osteocalcin, and other substances that make bones stronger. Strong musculoskeletal system is important for football, volleyball, basketball, wrestling, and other sports because it reduces the number of injuries.

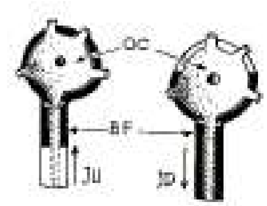

Figure1. Movements of the bone fluid in the lacunae and canals of osteocytes

OC – osteocyte; BF – bone fluid; JU – direction of movement of the bone fluid in the upper phase of the jump; JD – direction of movement of the bone fluid in the lower phase of the jump during landing

Activation of bone reproduction occurs during jumping (Rubin & Lanyon, 1984). At the same time, remodeling of bones occur not only in the process of plyometric exercises, but also during normal physical activity, especially in the submaximal power zone. Exercise effects the muscular system, tendons, joints, and bone not in isolation but in a complex way.

We seeanother vector of the influence of mechanical load on the process of reproduction and mechanostat of bones. In terms of biomechanics, it is clear that submaximal physical activity in anaerobic or mixed modes causes theaccumulation of lactic acid and other osmotically active substances. They redistribute the fluid in the body by retaining water in muscle fibers and intercellular substance. The existence of temporary functional muscle edema duringphysical activity is confirmed by scientists and athletes. At the same time, in bones, which are sounded by these muscles, there is “refueling” with fluid. Temporary non-pathologic retention of water is provided by hyaluronic acid and bone proteoglycans. The lacunar-canal system of the bone cannot stretch; thus, excessive water leads to a temporary increase in pressure on osteocytes and osteoblasts and deforms them by compression (Figure 2).

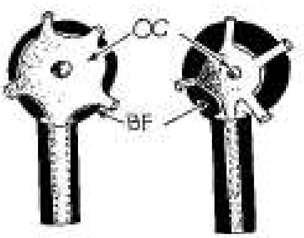

Figure 2. Movements of the bone fluid in the lacunae and canals of osteocytes
OC – osteocyte; BF – bone fluid

In the general mechanical-sensory mechanism of influence, there are at least three components: a) external pressure per surface unit of the bone, which causes micro-deformations (compression, sprain, and twisting), b) kinetic energy of shock motion-rocking of fluidin bone canals, which is caused by sharp motions or jumps, c) effect of osmotically active increase inthe internal pressure of bone fluid on bone cells in the lacunar-canal system.An additional osmotic factor is linked to a type of massage-compression of the osteocytes network and leads to their excitation. Activated cells of the bone produce more collagen, osteocalcin, and other substances of the bone that make it stronger.

Duringthe training process, most coaches have long used intense jumping exercises to improve the speed and strength of the athlete. However, plyometric load and proper nutrition are the most effective ways of preventing sports injuries. The frequency of injures in all types of physical activity affects the assessment of the level of health and training techniques and technologies. Currentlyin sport practice, the indicator of trauma per unit timeis already used. In particular, a previous study (Begizew et al., 2019) considered the risk factors related to lower limb injuries among 10 000-meter runners in Ethiopia. It has beenshown that the frequency of long-distance injuries was 0.35 injuries per 100 hof work or 3.54 per 1000 hof work. The most injured anatomical site was the knee joint (33.6%), andtension was the main cause (36.4%) (Begizew et al., 2019).

The most effective effect of plyometric loading on bone mechanostat occurs in children and adults, when the bones grow. Thus, in tennis players who train since childhood, the bone density of the working hand is3–4 times higher than that of the non-working hand (Kannys et al., 1995).The experiment performed on gymnasts, who trained for 3–4 years for8–10 hper week and gymnastswho trained for 1–2 yearsfor4–6 h, respectively, showed increased formation of the bone mass in selected areas of the skeleton in7-year-old athletes. Strengthening of bones in early childhood preserves skeletal integrity in later life (Zanker et al., 2003). The adaptive response of the bone to physical exercises depends on its frequency, duration, and intensity(the most important factor) (Rubin & Lanyon, 1984).

Long-term exercises increase bone mass not only in children but also in young people (Snow-Harter et al., 1992)and the elderly (Hoshino et al., 1996).Bonestrength depends on its shape, internal micro-architecture, density, and mass. In experimental studies, the *bone mineral density*indicator is widely used. It has been shown that the values of this indicator aremuch higher in athletes than those of people who do not train. Thus, male weightlifters have higher bone mineral density in lower and upper extremities (Karlsson&Obrant, 1993); female gymnasts – in lower and upper extremities and the spine (Dowthwaiteet al., 2006);football players – in the femur bone (Vicente-Rodriguez et al., 2004); tennis players – in the dominant hand if the training was started before the puberty period (Kannus et al., 1995), andmostly in the radial bone of the forearm (Ducheret al., 2006)if the puberty process is complete, and periosteum thickens (Haapasalo et al., 1996).Some aspects of the support system response to various physical activities have beenexplained by S. K.Grimston (Grimston, 1993).It has been determined that the load on the body exceeds the body weight: 12 times in gymnasts and 3–5 times in runners.

Plyometric training improves 30-meter running performance and the result of long jump in football players (*Yiannis Michailidis, 2015)*. Researchers (El-Ashker et al., 2019) evaluated the impact of an 8-week training programin two groups of men. The experimental group performed plyometric exercises for 8 weeks, and the control group performed traditional long jumps. Higher results in30-meter running, long jump, vertical jump, and biomechanical parameters of the long-jump movement (maximal vertical height, horizontal and vertical velocity at take-off, flight time, and take-off duration) were demonstrated by the experimental group. Plyometric training is recommended to improve sprinting and jumping abilities in jumping athletes.

Short-term plyometric training on sand and on hard surface improves indicators of force, endurance, balance, and dexterity. However, jumping on sand or soft surface causes less muscle soreness (*Amrinder Singh et al., 2014)*. Strength muscular adaptations in physically active men to the effect of short-term plyometric training

in deep diving on the sand with 48-hand 72-hrest time between workouts were studied. It is recommended to use 72-hrest time between workouts on a sandy surface(Abbas Asadi, 2015). Of particular note are the results of an 8-week training program on a vibrating device for residents of nursing homes (80+ years). It has been confirmed that training on a vibrating device is more effective for lower limb performance than without vibration (Álvarez et al., 2018).

In our opinion, the level of bone adaptive capacity in various sports depends on the magnitude of gravity, number of movements with high inertia and resistance, sharp change inspeed and direction of the movement, and short cushioning phase of landing and impact. Ultimately, the load on the skeleton is the pressure, an amount of force which impacts the unit area of the bone and the degree of deformation. Therefore, jumpingand other physical exercises with such characteristics are considered to be plyometric.

Prepubescent age is considered to be a sensitive period for sports activity on the formation of effective mechanostat.It has been confirmed that after puberty, 18 and 19-year-old boys maintain the positive correlation between the level of physical activity and the thickness of cortical bone tissue, bone mineral density of the spine, femoral neck, and forearm (Lorentzon et al., 2005). The effect was higher in children who started training before the age of 13 years old with 4 hper week. Jumping exercises enhanced the indicators of the bone mineral density in 8-year-old children by 3.5%comparedto those inthe control group. After completing theprogram, bone mineral density in the experimental group remained higher than that of peers in the control group for 7years as an aftereffect (Fuchs, 2001; Gunter et al., 2008).

The motor apparatus that is formed in childhood retains its strength characteristicsin later life after completing sport exercises. The five-year observation has shown that with supportive physical activity, former tennis players maintain good bone mass (Kontulainen et al., 2001). In female gymnasts, bone mass does not change for 12 years after completing active training (Zanker et al., 2004); in runners, the bone mass drasticallydecreases a year after the end of training (Lehtonen-Veromaa et al., 2001); in football players, extremely high rates of leg strength decreases after the end of exercises and the risk of fractures is closer to those of normal people (Karlsson et al., 2000).

Excessive and strenuous exercises reduce testosterone production and weaken male bones.Studies by two groups of researchers have shown that 20 and 40-year-old triathletes have lower level of total and free testosterone compared to the control group(Wheeler et al.,1984; Smith & Rutherford, 1993).

In 35–45-year-old women, intense jumping, running, and walking three times a week for 60 minfor 1 year increased mineral density of the femur and trochanter. Anincrease in bone mineral density was higher after jumping and running activities than after walking and depended on the number of exercises(Vainionpaaet al., 2006, 2007).

Increased bone fragility and osteoporosis are common in 47–50-year-old women with estrogen deficiency and in young women with excessive physical exercises, energy expenditure, and malnutrition, i.e., so-called sport triad. Menopause in women is accompanied by loss of bone mineral density and bone mass. However, weightlifting for a year in women with early menopause at the age of 52 years led to a small increase in bone mass ofthe spine (+0.7%), and in the control group – to a decrease (−0.7%)(Maddalozzo et al., 2007). Stem cells perform the function of progenitors of bone cells. Most of them are located in adipose tissue. Later, it has been determined (Ubago-Guisado et al., 2019) that there is a correlation between bone mineral density and the content of some minerals with a fat mass of 55 healthy and sedentary women.

The ability of the bone to adapt to physical exercises decreases with age; thus, the problem of intensity of non-traumatic threshold stimuli that initiate bone remodeling in the elderly is very important (Kallinen & Markku, 1995). With age, some structures of the bone degrade, and others grow.In particular, as a result of 20-year studies of women who crossed the line of menopause, a decrease in the thickness of the inner spongy part of the bones was recorded. At the same time, the growth of external periosteum was revealed, which may be considered as compensatory protection against fractures (Duan et al., 2001). Instead, moderate alcohol consumption reduces bone loss in postmenopausal women by increasing circulating estrogen levels, but adversely affects immature skeleton (Russell et al., 2001).

In our opinion, the processes of building bone and muscle mass occur in parallel according to a similar program, and the processes are intertwined. The mechanism of their implementation is based on the general biological laws of regulation on the principle of feedback. In abbreviated form, we distinguish the following sequence of adaptive responses to plyometric exercise.

The 1st stage – the main sensors of mechanical impact, which detect the nature and degree of load on the musculoskeletal system (maximum, submaximal, moderate, plyometric, and isometric); type of nervous, respiratory, endocrine response of body systems at molecular, cellular, and organismal levels (adaptation toaerobic, anaerobic, and mixed modes of operation); cascade and level of catabolic changes in the system (balancing the strength of the stimulus with the scale of response to physical stress); features of metabolite utilization; speed and amplitude of re-synthesis of consumed energy, construction, and regulatory substances during anabolic processes of the recovery process are as follows: in the bones – a network of osteocytes (partly osteoblasts); in the muscles – neuromuscular spindle, in the musculoskeletal area – neuromuscular-tendon spindle, in the tendon area – neuromuscular spindle. In general, they balance the quantitative and qualitative indicators of physical activity with the level of response to them. Physical activity, as a type of stress, leads to the breakdown of energy compounds. At the same time there is disintegration of structural and regulatory substances of these tissues. *In bones*, dedicatedmacrophages destroy the organic and mineral parts; in *muscles*, actin and myosin filaments of myofibrils, collagen, elastin, and chondroitin-sulfur filamentstructures for their recovery and further increase of muscle mass by hypertrophic break down.

The 2nd stage – load metabolites accumulate, which show an anabolic effect on their own or by stimulating the formation of other regulatory substances. In bones, there is a non-pathological accumulation of calcium ions, phosphorus, amino acids, and collagen fragments. Eventually, bone breakdown products enter the bloodstream and muscles. Among the metabolites, the amino acid L-arginine is essential because the enzyme NO-synthase forms nitrogen (II) oxide (NO) from it.The NO molecule relaxes vascular smooth muscles,increases blood flow, and activates the process of neurotransmitters and the transmission of nerve impulses. Nitric oxide and insulin-like growth factors inhibit genetically programmed death (apoptosis) of osteoblasts and osteocytes and osteoclast activity. Instead, muscles increase the content of lactic acid, amino acids, peptides, and creatine, which also enter the blood and bones.

The 3rd stage – metabolites of physical activity perform anabolic action through a system of biochemical mediators (in particular, the system of adenylate or guanylatecyclases) and activate certain genes and reactions of reduction or super-recovery. In bones and muscles, Ca^{2+},cAMP, cGMP, and NO lead the corresponding enzyme protein kinases into active state. Protein kinases phosphorylate chromatin histone proteins, enzymes, hormones, and membrane proteins (receptors, ion channels, and transporters). Modified chromatin regulatory proteins include or activate certain genes in osteocytes, osteoblasts and chondrocytes. The biosynthesis of bone reproduction factors – osteoprotegerin (OPG) and insulin-like growth factors (IGF) is enhanced. Osteoprotegerin has an inhibitory effect on osteoclasts and, thus, slows down the breakdown of bone tissue. Instead, the osteoclast activator cytokine (RANKL) stimulates bone resorption, osteoporosis, and fractures. Systematic plyometric training produces more osteoprotegerin and strengthens bones, and with reduced physical activity and immobilization, the synthesis of bone destroyer cell receptor activator (RANKL) increases, and there is a risk of fracture.Insulin-like bone growth factors (IGF-I, II) are produced by osteoblast precursors and osteoblasts. They can also originate from the circulatory system. Sex hormones, calcitonin, somatotropin, and insulin affectthe anabolic and growth effects. Each type of exercise has a targeted effect on certain types of bone, cartilage, and muscle fiber cells and forms specific adaptations.

In particular, in white fast muscle fibers, an increase in muscle mass, strength, and power occursowing to the biosynthesis of myofibril proteins (actin and myosin), and the development of strength and speed without increasing body weight is realized by increasing the synthesis of ATPase, and creatine phosphokinases, which areenzymes that produce large amounts of "fast" energy. This type of capacity building is important in weightlifting, powerlifting, wrestling, boxing, martial arts, and other sports where there are weight categories.

In red slow muscle fibers of marathon runners, triathletes, runners, swimmers, and rowers, the adaptation is aimed at increasing aerobic endurance. This increases the synthesis of respiratory chain enzymes in the membranes of mitochondria, fat oxidation, Krebs cycle, the formation of hemoglobin and myoglobin, increasing the rate of muscle capillarization. Gray intermediate muscle fibers increase the synthesis of enzymes of glycolysis, lactic acid utilization, means of stabilizing the pH of the environment and everything that is needed in the anaerobic–aerobic zone of physical activity. In bone and joint osteoblasts, osteocytes, and fibroblasts, the rate of biosynthesis of collagen, osteocalcin, elastin, hyaluronic acid, and bone mineralization is accelerated by the formation of the main mineral – hydroxyapatite and the restoration of bones, tendons, and joints.

Conclusion

1. Plyometric exercise is a powerful natural way to maintain the health of bones, tendons, joints, and other elements of the human musculoskeletal system.

2. The expressed adaptive processes of strengthening of the mechanostatoccur in the bones thatare exposed to high and long plyometric loading.

3. Strengthening of bones can occur owing to one, several, or all ways of their reaction to compression, tension, or various plyometric movements and osmotically-caused deformations. Among them are shape, internal microarchitecture (geometry), density, mass, and thickness of individual components.

4. Experimental studies using only one indicator of mechanostat evaluation, such as *bone mineral density*, cannot be a definitive argument to deny the positive effect of exercise or sport on bone strength because adaptation strategies aremultifaceted.

5. Prepubertal age is a sensitive period for the influence of physical activity on the formation of an effective mechanostat of bone tissue and the health of the musculoskeletal system. Formed in childhood, high bone mass will be a preventive protection against osteoporosis and injury in old age.Therefore, when there is an

insufficient number of gyms, stadiums, and sections for mass sports, physical education lessons with plyometric load should be a mandatory component of educational programs of preschool, primary and secondary schools.

6. The heterogeneity of the conclusions of experimental work on the effects of exercise on the musculoskeletal system is due to different types of exercise, age of the studied groups, the initial level of their physical fitness, nutrition, and living conditions. To objectify the assessment of different plyometric bone mechanostat improvement programs, unified exercise techniques should be developed and used as standard platforms for different age groups.

7. Generalization of the results of experimental studies and observations of motor activity and training process indicate that the effect of physical activity on bones is realized through at least three different effects: 1) pressure per unit surface of bone caused by microdeformations (compression, tension, and twisting); 2) the movement of bone fluid, which is a type of massage of the network of osteocytes and osteoblasts; 3) the effect of osmotically active increase in the internal pressure of bone fluid on bone cells in the lacunar canal system.

8. The processes of building bone and muscle mass are intertwined. The mechanism of their implementation is based on the general biological laws of regulation on the principle of feedback.

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