VOLUME 69 | ISSUE 3 | JULY - SEPTEMBER 2018

Bone tissue adaptation to muscular loads

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ABSTRACT

This is a literature peer review of muscular loading influence to the functional bone adaptation. Reception of mechanical signals produced by either muscle forces or gravity affect bone formation. Muscle forces are capable of promoting functional bone adaptation. A number of clinical scientific reports points out that during exercise bone increase, muscle forces have a leading role in creating the mechanical stimulus. Muscle forces provide a significant amount of applied force and therefore are the main stimuli that lead to the adaptive response of the bone.

Keywords: Bone adaptation; bone tissue; gravity; mechanical stimulus; muscle forces

The Mechanostat Theory of Frost

Harold Frost proposed the theory of a bone homeostatic monitoring mechanism, which is liable for detecting alterations in the mechanical requirements applied on it. [1] Bone mass and structure are changed in order to achieve the best possible response to these new mechanical requirements. [1] In particular, Frost put forward that there are loading thresholds that monitor the mechanical usage of bone, changing its architecture when these loads are increased or decreased.[1] Underneath a ceratain mechanical usage threshold, bone tissue is absorbed and bone mass is decreased. [1] Over a different threshold in which mechanical loads are larger than typical peak strains, there is bone mass increase and therefore mechanical strength increase. [1] Accordingly, there is an inherent mechanostat, which adjusts the functional bone adaptation. [1]

Mechanical stimulus

Harold Frost suggested that the stimulus, which causes functional bone adaptation, depends on the magnitude of deformation that has been caused in it. Deformation is defined as the change in bone length compared to its original length or the alteration of particular characteristics of bone tissue, which occurs with loading. [2,3] Bone mass is maintained and adapted to mechanical deformation mainly

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as a result of muscle contraction. [4] Long bones deformation is achieved through muscular activity. [4] Forces that cause bone adaptation are associated with the action of muscles and not with simple gravitational forces. [5] Therefore, muscle mass and strength are correlated with bone strength. [6]

Bone modeling & remodeling

Process of bone modeling involves the independent action of osteoclasts and osteoblasts on the surfaces of bone, whereby new bone is builded along certain surfaces and removed from others. [7] Thus, the process of bone formation and resorption affects the size and shape of bones and therefore is a critical process for the remodeling of long bones as they grow and lengthen during adolescence. [7]

Bone remodeling is a local process involving the combined double action of both osteoclasts and osteoblasts, in which initially the osteoclasts absorb a small amount of bone and then the osteoblasts, in the specific site, form and mineralize new bone. [8] Generally, the amount of bone formed is equivalent to the amount of bone absorbed in each bone remodeling unit, with the exception of disuse. [9] The resorption period averages 30 - 40 days and is followed by bone formation lasting 150 days. [10]

Functional bone adaptation

Harold Frost introduced the term “mechanostat” to describe the mechanism of functional bone tissue adaptation. The mechanostat is a homeostatic regulative mechanism of the bone, which modifies bone structure, in response to changes that occur due to mechanical requirements applied in the bone. [1,9] It has been shown that bone mass is reduced in the absence of usual loading, while it is increased when loading is greater than the usual. [11,12]

An experiment with 26 adult female rats investigated the effect of mechanical loading, at separate time periods, on the bone structure and evaluated the biomechanical properties of the ulna after 16 weeks of loading. [13] The right ulnas of 26 adult female rats were subjected to 360 cycles of loading / day, with a maximum force of 17N, 3 days / week for 16 weeks. [13] In half of the rats, (n=13), the 360 daily loading cycles were given in a single period (360 x 1) without a break. [13] The other half of the rats (n=13) were given 90 cycles of four times a day (90 x 4), with a 3-hour break between the loading periods. [13]

In the rats that participated in the program of 360 cycles loading x 1 times / day, the ultimate force of their ulna was increased by 64% whereas those who participated in the program of 90 cycles loading x 4 times / day, increased by 87%. [13] Thus, mechanical loading was more effective in improving the biomechanical and structural properties of the bone, when the loads were applied in separate periods, segregated by pauses (90 cycles x 4 times / day), compared to the loads applied in one session (360 cycles x 1 time / day). [13] Significant increases in bone biomechanical properties occurred despite the very low benefits of 5-12% in bone density and bone mass, of 26 rats ulnas. [13] These findings demonstrate that a small increase in bone density and bone mass, which is put where it is mechanically optimal, as well as intermittent loading and not in a single period, can lead to significant biomechanical benefits. [13]

The role of Menopause to mechanostat

The outset of menopause results in the reduction of bone mechanical sensitivity which occurs when women become older. In an experiment, it was shown that estrogen regulates the bone cells mechanosensitivity through the synthetic prostaglandin pathway. [14] Hence, at the outset of menopause the reduction of estrogen, can make bone less sensitive to mechanical stimulus.

A study has demonstrated that moderate to strong intensity exercises, performed at high speed for short periods of time, either on water or on the ground, can be part of a program to prevent and treat postmenopausal osteoporosis. [15] The mechanical vibrations have been prooved useful for bone microarchitecture, for increase bone density and strength and for improvement of physical function. [15] Activities aimed at increasing muscle strength, body balance and improving the proprioception of postmenopausal women, with the aim

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Fig. 1: *Humerus diaphysis bone associated with throwing the ball was more powerful compared to the one which did not participate in the throws. [16]*

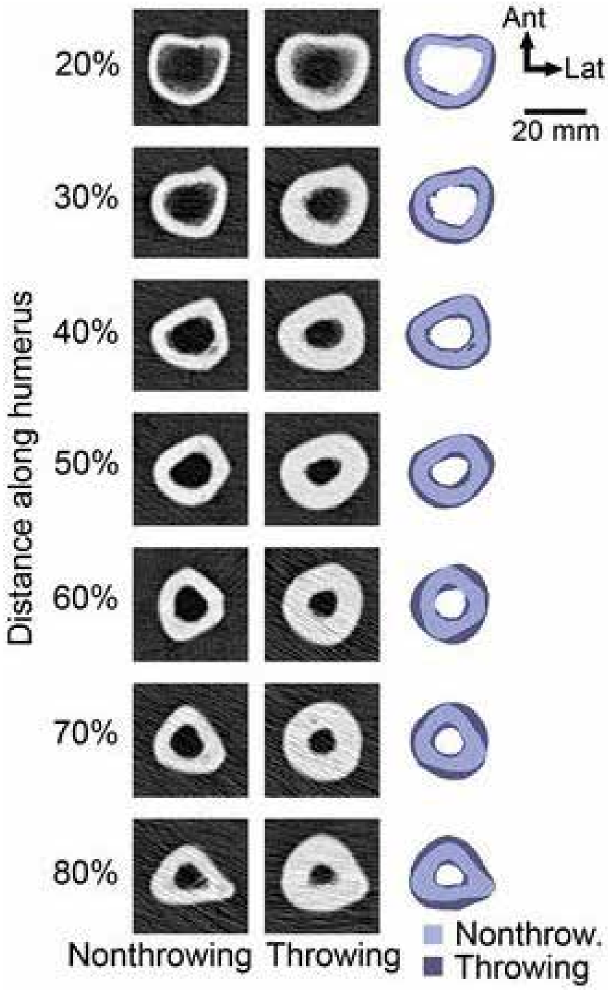

Fig. 2: *More important benefits were observed in cortical bone mass and thickness and less medullary cavity (medullary canal) extension of the ball throwing arm than the not throwing arm. [16]*

of preventing falls and fractures, should be recommended. [15]

Ideal time to load bone tissue

In a study that was conducted, the differences in the properties of the humerus diaphysis bone in throwing the ball arm and of which did not throw the ball, of 103 professional baseball players, at different stages of their career, were compared with the properties of prevalent and non-prevalent arm of 94 persons of the control group. [16] In the humerus diaphysis bone associated with throwing the ball, extreme loads were caused and bone strength almost doubled (**Figure 1**). [16] After the cessation of sports activities, the benefits to cortical bone mass and thickness, which acquired during the youthful physical activity (**Figure 2**), were gradually lost due to larger extension of the medullary cavity (medullary canal) and greater cortical bone "trabecularization". [16] Nonetheless, half of the increase in bone size and one-third of improvement in bone strength that occurred from physical activity associated with throwing the ball during juvenile times, were maintained throughout the rest of the life of veteran athletes. [16] Former professional baseball players who continued to throw balls during their ageing retained a part of cortical bone mass and most of the benefits in humerus diaphysis bone strength due to physical activity during their youthfulness, as a result of lesser extension of the medullary cavity (medullary canal) and lesser cortical bone "trabecularization". [16] These results revealed that the theory of "use it or lose it" is not fully practicable to the human skeleton and that physical activity should be encouraged during the young age, aiming at the bones health throughout their lives of people, with an emphasis on optimizing bone strength and size instead of increasing bone mass. [16] Furthermore, the above results demonstrate that physical activity should also be encouraged throughout ageing, in order to restrict the bone structure degeneration. [16]

Ideal loading features

A study carried out on immature bones of female rats investigated the effects of training by jumping on bones morphological and mechanical properties.[17] Five week old rats were divided into 6 groups, 1 control group and 5 groups were trained at 5, 10, 20, 40 and 100 jumps per day. [17] Rats were trained 5 days / week for 8 weeks and jump height gradually rose to 40 cm. [17] In the group that followed 5 jumping / day, the femur and tibia had a significantly higher percentage of dry weight, without fat, per body weight and in fracture tests were able to withstand higher peak loads than rats in the control group. [17] While it was observed a modest proclivity to increase depending on the number of leaps per day, however there were few variations in morphological and mechanical bone parameters amongst the groups that followed 10, 20 and 40 jumps per day. [17] These data show that a small number of loads per day are sufficient to grow bone formation in response to workout. [17]

Exercise in the elderly

An eight week study aimed at researching the influence of a balance exercise and a program of elastic resistance exercises in muscular strength and elderly balance, in order to propose an effective intervention to prevent falls in this age group, which is at the highest risk of falling. [18] The study involved 55 elderly people who were divided into three groups: the first group followed a program of equilibrium exercises, the second followed a program of resistance exercises and the third was the control group. [18] In the group that followed a resistance exercises program, there were major ameliorations in strength of hip flexors, hip extensors, hip abductors, knee flexors, knee extensors, ankle dorsiflexors and ankle plantar flexors and balance of elderly. [18] In the group that followed a program with balance exercises, there were important enhancements in strength of all muscle groups apart from the knee flexors and ankle plantar flexors. [18] This study has proven that a program which uses either equilibrium exercises or elastic resistance exercises is efficient to enhance elderly muscle strength and balance in order to reduce risk of falls in them. [18]

Latest clinical data

An experiment carried out with 40 virgin female mice up to fourteen weeks of age, explored the skeletal consequences of muscle inhibition caused by Botox in cage control and tail suspended mice.[19] Each animal was injected with Botox in the right posterior leg and with vehicle in the left posterior leg. [19] After right posterior leg muscle inertia, animals were randomly separated into two groups: the first was the cage control and in the second, mice tail suspended for six weeks. [19] It was found that skeletal effects of Botox-provoked muscle inertia are not only due to retraction of gravitational forces.[19] Withdrawal of gravitational forces of the posterior legs through tail suspension caused a bone mass decrease due to diminished periosteal bone formation and intensified endosteal bone reabsorption. [19] The raise in endosteal bone absorption was remarkable by a considerable increase in medullary cavity (medullary canal) and a decrease in cortical area and cortical thickness. [19] Muscle inertia caused by Botox on tail suspension aggravated these skeletal alterations with both of removal of gravitational forces and muscle inertia had the largest damaging action on the skeleton, caused the least profits in midshaft tibial bone mass, cortical area and cortical thickness, greatest profits in midshaft tibial medullary cavity (medullary canal) and lowest proximal tibial trabecular bone volume fraction (**Figure 3**).[19] These results prove Botox-provoked muscle inertia triggers further skeletal influence than those caused only by excised gravitation-

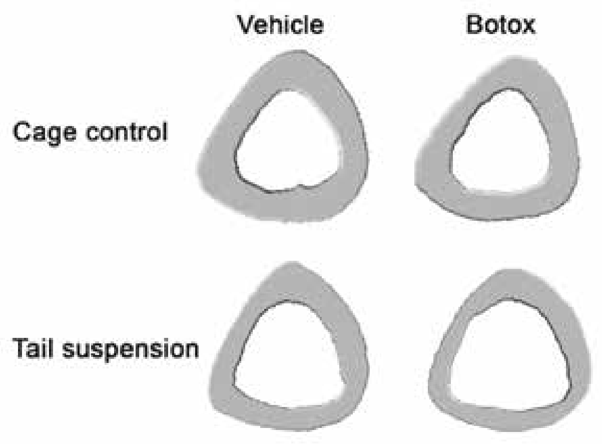

Fig. 3: The influence of gravitational and muscular interference on midshaft tibia structure. It is remarkable the decrease of tibia bone mass and cortical bone thickness, both in tail suspension and muscle inertia caused by Botox, due to the considerable increase in medullary cavity (medullary canal). These skeletal alterations deteriorated in tibiae subjected to tail suspension and Botox-provoked muscle inertia simultaneously. [19]

al forces.[19] Therefore, muscles have an immediate influence on bone tissue.[19]

Conclusions

Mechanical loads exerted on bones are distinguished by forces of gravity and muscular forces and determine bone architecture, structure and adaptation. Bone tissue has an inherent mechanostat, which adjusts the functional bone adaptation.

Muscle mass and strength are correlated with bone strength. A small increase in bone density and bone mass - gained easier with intermittent loading and not with a long but single loading period - can lead to significant biomechanical benefits. A small number of loads per day are sufficient to build bone in response to workout.

Physical activity should be encouraged throughout ageing, in order to prevent bone structure degeneration. A program which uses either equilibrium exercises or elastic resistance exercises is efficient to enhance elderly muscle strength and balance in order to reduce the risk of falls.

Muscular loads constitute the main stimulus which leads to functional bone adaptation.

Conflict of interest:
The authors declared no conflicts of interest.

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Kokkinias AD, Triantafyllopoulos KI. Bone tissue adaptation to muscular loads. *Acta Orthop Trauma Hell* 2018; 69(3): 126-131.

ΠΕΡΙΛΗΨΗ

Η παρούσα εργασία αποτελεί μία βιβλιογραφική ανασκόπηση της επίδρασης των μυϊκών φορτίων στη λειτουργική προσαρμογή του οστού. Η λήψη μηχανικών σημάτων με συγκεκριμένα χαρακτηριστικά, το σύνολο των οποίων μπορεί να παραχθεί είτε από μυϊκές είτε από βαρυτικές δυνάμεις, απαιτείται στον προκαλούμενο από τη φόρτιση οστικό σχηματισμό. Οι μυϊκές δυνάμεις είναι ικανές να προωθούν τη λειτουργική προσαρμογή του οστού. Αρκετές κλινικές επιστημονικές αναφορές επισημαίνουν ότι στην προκαλούμενη από την άσκηση αύξηση του οστού, οι μυϊκές δυνάμεις διαδραματίζουν κυρίαρχο ρόλο στη δημιουργία του μηχανικού ερεθίσματος. Οι μυϊκές δυνάμεις παρέχουν ένα σημαντικό ποσό της ασκούμενης δύναμης και επομένως συνιστούν το κύριο ερέθισμα που οδηγεί στην προσαρμοστική απόκριση του οστού.

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Προσαρμογή του οστού, οστίτης ιστός, βαρύτητα, μηχανικό ερέθισμα, μυϊκές δυνάμεις.