EFFECTS OF EXERCISE AND TRAINING ON SKELETAL DEVELOPMENT IN HORSES

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The main role of the equine skeleton is to provide structural support. Conformation determines the functional integrity and success of the gaits of athletic horses. The bones of the skeleton determine conformation or balance and structural correctness. The relationships of alignment, lengths, and angles of the bones of the skeleton have tremendous effects on the athletic ability and long-term soundness of horses. Bones must oppose muscular contraction to create movement and withstand the forces of the applied loads resulting from mass, gait, speed, and interactive forces with ground surfaces. Bone is also critical for protecting internal organs from injury. The skeletal system also includes tendons, ligaments, and cartilage. Each element of the musculoskeletal system must be functioning correctly in order for the horse to travel soundly. Acute malfunction of the skeletal system is most often associated with injury to the bones of the lower limb.

A horse galloping at race speed will place three times its body weight as force on the lower limb. There is a complicated support system for the skeleton; muscles, tendons, ligaments, cartilage, joint lubricants, and hoof structures help dissipate the forces of locomotion. But ultimately the strength of the bones of the legs must bear the loads created by exercise and training. Strength of bone is derived from a mineralized cartilaginous matrix. Strength is defined as the amount of force a bone can withstand per unit area.

When measuring breaking strength or the amount of force applied to a bone before failure, an important factor, the area moment of inertia, must also be calculated. The moment of inertia increases as the distance from the neutral axis (mechanical center) to the outermost point increases. Basically, as the bone gets bigger in diameter it gets stronger.

The bones of the skeleton are a dynamic tissue and are therefore responsive to forces placed upon them. Bone also responds physiologically to changes in calcium, phosphorus, and magnesium homeostasis and houses the bone marrow (site of red blood cell synthesis). The remodeling of bone in response to exercise is the result of signaling bone cells to remove bone via osteoclasts and then to build bone via osteoblasts.

The remodeling sequence includes (1) osteoclastic resorption; (2) preosteoblastic migration and differentiation into osteoblast; (3) osteoblastic matrix (osteoid)

formation; and (4) mineralization (Mundy, 1999). Mature compact bone remodels in pockets known as bone-forming units. These pockets function independently and can be located throughout the skeleton. The remodeling of each pocket takes up to four months. The independent characteristics of bone remodeling suggest that the activation of the remodeling sequence can be controlled by local events in the bone microenvironment. The new bone is called the bone structural unit (BSU). Compact bone reacts more slowly to remodeling signals and is controlled by parathyroid hormone and 1, 25-dihydroxy vitamin D_3. Cortical bone comprises more than 80% of skeletal bone. Cancellous bone also remodels in response to local force stimuli, but because it is labile and subject to rapid turnover, it is also very responsive to mineral homeostasis, particularly changes in blood levels of calcium and phosphorus. Part of its responsiveness is related to its association with bone marrow, which has a high concentration of osteotropic cells (cytokines).

One theory of bone remodeling is that osteoclastic precursors recognize a change in the mechanical properties of bone, which signals a need for increased structural strength of new bone. While the exact signal for remodeling is unknown, the effective signal is strain. Strain is defined as the ratio of the change in length or dimension to the original dimension. Strains result from deformation of an object by a force. Force is mass times acceleration. Forces on bone can be applied in tension, compression, or shear. Shear forces result when there is bending or torsion and layers of material slide against each other. The minimum effective strain for modeling is reported to be 1500 to 3000 µε. The threshold for remodeling is thought to be much lower, between 100 and 300 µε. There also appears to be an optimum strain rate or number of strain cycles for maintenance of skeletal strength (Dalin and Jeffcott, 1994).

Exercise in Young Growing Horses

Initial mineralization of the cartilage models of the bones of foals takes place in the last three months of pregnancy and continues at an accelerated pace through the first year of life. The skeleton of the newborn foal contains only 17% of the adult bone mineral content. It consists mainly of cortical or compact bone and cancellous or trabecular bone. Figure 1 illustrates the degree of mineralization or the percentage of compact bone in relation to cancellous bone when compared to adults.

The two types of bone of most concern for growing horses are woven bone and lamellar bone. Woven bone is rapidly formed and characterized by loosely packed, large diameter collagen bundles. Woven and lamellar bone have osteocyes that are located within lacunae and interconnected via a network of fine canaliculi. Thicker collagen fiber bundles lie parallel to each other within the plane of each lamella (Figure 2). The orientation of collagen fibers can vary. Lamellar bone formation is a slow process, as lamellae are deposited along the long axis of the bone. In order for the bone growth to keep pace with the rapid growth in foals a

combination of bone types are found. Fibrolamellar bone consists of circumferential layers of woven bone separated by radial struts (Riggs and Evans, 1990). Rather than concentric layers of lamellae forming around the entire bone, there are branches that radiate out from the center of the bone, similar to the branches on a tree. This allows the bone circumference to expand rapidly and lamellar bone is filled in at a slower rate.
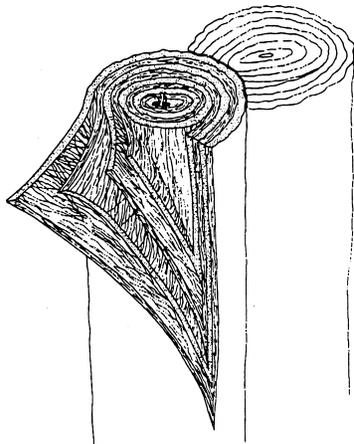

Figure 1. Degree of mineralization or percentage of compact bone in relation to cancellous bone when compared to adults.
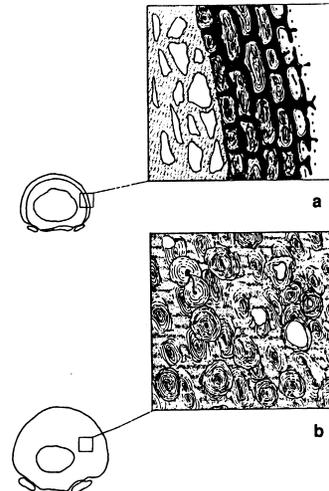
Figure 2. Thicker collagen fiber bundles lie parallel to each other within the plane of each lamella.

Recent research supports the idea that bone morphology and mechanical and chemical properties can be affected by exercise or the lack of it from birth throughout the life of the horse. Barneveld and van Weeden (1999) reported significantly lower (37 ± 4%) bone density of the third tarsal bone of five-month-old foals that were housed in box stalls compared to pasture-raised and box-raised foals that were sprint-trained from one day of age. In a similar study from The Netherlands, the effects of exercise on the developing bones of newborn foals through weaning were examined. At weaning eight foals from a pasture group, a box stall group, and a box stall-sprint trained group were euthanized. The remaining 19 foals on the study were housed together in a large covered area with access to a paddock (van de Lest et al., 2003). The authors concluded that the bone mass (cross-sectional area and bone mineral density from subchondral bone at the femoropatellar joint) for the pastured horses and the sprint-trained horses was similar and significantly higher than the box-stalled group. However, the authors caution against the sprint training because of an inverse relationship between the bone morphogenic enzymes alkaline phosphatase and tartrate-resistant acid phosphatase and possible long-term effects. After six months of identical exercise, there were no differences between the groups.

Bell et al. (2001) kept 17 weanling Arabian horses either in stalls, on pasture 12 hours/day, or on pasture 24 hours/day for 56 days. Nutrient intakes were standardized via the use of ad libitum alfalfa hay in the stalled group. Radiographs were taken at 28-day intervals along with morphometric measurements. Radiographs were analyzed with photodensitometry. The partial-pasture turnout group and the full-pasture turnout group had increased bone mineral contents. Cannon bone circumference increased in both the pasture group and the partial pasture groups, but not in the stalled group.

Firth and coworkers (1999) subjected Dutch Warmblood foals to different exercise regimens. The foals were either box confined, box confined and sprint-trained daily, or kept at pasture until they were five months old. From six to 11 months, half of the horses were confined in a stall with daily turnout. Foals that were trained and turned out had greater bone density than confined foals. Foals with lower bone density had higher osteochondrosis scores and showed the most variability in growth rates during the first five months. At 11 months of age, there were no differences in bone density between groups. Raub et al. (1989) exercised a group of 10 Thoroughbred or Quarter Horse weanlings for 111 days and compared bone mineral content (BMC) estimated by photodensitometry to a group of 9 horses housed in stalls at night and turned out in pens during the day. The exercised group was trotted at a speed of 3.6 m/s starting at a distance of 0.4 km and gradually working up to 4.35 km/d. They were exercised five times each week. At the end of the 111-day period, the exercise group had 25% more estimated bone mineral content in the cannon bone than the non-exercise group.

Hoekstra et al. (1999) divided sixteen Arabian long yearlings that had been on pasture into two groups. One group was housed in box stalls while the second group was maintained on pasture. Radiographs were taken every 28 days for densitometry. Blood samples were taken every 14 days. After an 84-day pre-training period, six horses from each group were placed in a 56-day training period. Stalled horses had decreased BMC estimates at days 28, 56, and 140. Serum osteocalcin concentrations were lower at day 14 ($p < 0.05$) and urinary deoxypyridinaline (a bone resorption indicator) was greater at day 28. Nielsen et al. (1997) at Texas A&M University placed 53 eighteen-month-old Quarter Horses in race training. They were broken to ride and trained in a typical race-training program for 17 weeks. The horses then entered an 18-week racing period during which they were raced every other week for a total of nine races. Radiographs were taken of the left metacarpal on day 0, 62, 104, and 244. Decreases in radiographic bone aluminum equivalence (RBAE) of the lateral, medial, and dorsal cortices were observed from day 0 to day 62. After the initial decrease in estimated bone mineral, the RBAE increased by day 104 and day 244. The authors report that the introduction of speed work corresponded to the lowest RBAE readings.

Firth et al. (2000) summarized a series of studies examining the effects of training on two-year-old Thoroughbred fillies. They were treadmill trained at a gallop three times a week for 4.5 to 18 months. These trained fillies were compared

with control fillies that were exercised only at a walk. In the trained horses, changes in bone mineralization were detected within three months. The changes consisted of thickened trabecular bone in the subchondral area, the cuboidal bones, and specific areas of the epiphysis of long bones. A companion study looked at the effects of exercising fillies on a training track compared to Thoroughbred fillies housed in stalls with turnout on dirt yards during the day. The training consisted of four weeks slow cantering, four weeks fast cantering, and then four weeks fast cantering with fast gallops included twice a week. Researchers reported increases in bone density of 36.8% in epiphysis of the metacarpal.

Sherman et al. (1995) measured the breaking strength, cross-sectional area, and area moments of inertia in the cannon bones of 24 Thoroughbreds in various stages of training from two to four years of age. Horses with the most training had greater cross-sectional areas and area moments of inertia. Greater cross-sectional areas and moments of inertia correlated with greater breaking load.

Thoroughbred Race Training

The strength and ability of the bone to resist a load or force placed upon it is dependent on the quality of the bone materially and on the size and shape of the bone. Davies and McCarthy (1994) reported that strains on the dorsal aspect of the third metacarpal increased linearly with speed and were higher in yearlings than mature racehorses. Nunamaker et al. (1990) reported that the third metacarpals of young Thoroughbreds have a fatigue life of 50,000 cycles when tested at strains recorded in young horses in training and more than a million at lower strains recorded in older horses. The authors state that clinically it is common to observe fatigue fractures occurring five months into training which should correspond to roughly the time it takes to complete 50,000 strides in typical training programs.

Davies (2001) further demonstrated differences between individual horses and between mature racehorses and naive Thoroughbreds that were significantly related to the geometry of the midshaft of the cannon bone. Horses with greater cross-sectional area and more bone deposited in the dorsal cortex had lower peak strains. The speed of ultrasound measurements is known to be faster in denser bones; however, Davies (2002) reported that ultrasound readings were faster in bones with higher strains. Davies (2002) stated that higher strains associated with stiffer and denser bones were not expected because faster ultrasound readings are associated with higher bone mineral contents. The author states that the remodeled bone deposited on the dorsal cortex of the third metacarpal is more porous than the original growth. The rapidly produced bone resulting from remodeling does not have the circumferential lamella organization of primary osteons; however, the increased strength associated with the changes in shape and increases in bone deposited in the areas of highest strain offsets any losses in strength associated with decreases in bone mineral in that area. Overall, the bone mineral content of the bone was not changed, but the distribution of the mineral was.

Remodeling is dependent on peak strain rates, though there is a maximum number of peak strain rates a bone can withstand. Peak strain rate can be altered with training but still may be limiting. Davies (2002) states that interaction between the size and shape of the bone and the quality of bone determines how much bone mass is needed to withstand racing speeds in an individual horse.

Boston and Nunamaker (2000) designed a survey study to determine the degree to which components of the training programs of two-year-old Thoroughbreds influenced their susceptibility to fatigue injury (bucked shins). They found that if more training effort was directed at short-distance breezing (15 m/s for 0.24 km/week) and less to long-distance galloping (11 m/for 7.19 km/week) there was a significant reduction in the incidence of fatigue fracture. The exact type of exercise needed to develop young equine athletes for sustained sound performance will need to be established for all disciplines. Evidence suggests that early free exercise combined with training programs started in horses under three years of age will produce long-term effects, both positive and negative, depending on the ultimate performance and characteristics of breeds and individuals within breeds.

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