K7: Tendons Control Muscle Forces And Bone Adaptation: Cybernetics Of The Tendon-Muscle-Bone-Unit

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The main function of bone is to supply mechanical support for locomotion. The largest forces that act on bone are caused by muscle contractions and transferred to the bone via tendons. Due to lever arms, jumping on one leg causes forces that can be more than 10 times the body weight. According to Hooke's law the force causes a proportional deformation (strain). To fulfill its mechanical function bone must be able to adapt its strength to changes in the magnitude and direction of muscle forces so bones do not fracture or cause pain during voluntary muscle contractions (mechanostat). Alike tendons must be able to adapt to increasing muscle forces. In contrast to bone this adaptation process occurs only until the end of the growth phase and is not (or only to a small amount) observed in adults.

Due to the lever arms (typically 3:1 between toes and the rotation axis of the ankle joint and achilles tendon and the rotation axis of the ankle joint) muscle force must be 3 times the body weight to keep the heel from the ground. The body weight adds to this muscle force, so during a static stand on the forefoot 4 time body weight rests on the tibia. During one legged hopping the ground reaction force is typically 3 - 3.5 times the body weight. This means a force of 12 to 14 times the body weight acts on a tibia during one legged hopping. For a body weight of 80 kg that would be almost 11000 Newton. The typical cortical cross sectional area of tibia and fibula at 14% of the tibial length (the position where the bone mass has its minimum along the tibia) is around 350 mm². So the stress is ca. 32 N/mm². The elastic modulus of bone material is ca 15 GPa or 15000 N/mm². So the tibia and fibula would experience a deformation of 2100 μstrain or 0.21% of its original length during hopping on one leg. The ultimate strength for bone is ca 180 MPa. So there is a safety factor of 5.6 between the normal physiological load and the fracture limit of bone. The same considerations for the force on the Achilles tendon during one legged hopping would result around 8400 N for a person with a body weight of 80kg. The tensile strength of the Achilles tendon is given in the literature as 120 MPa. So in order not to rupture the cross sectional area of the Achilles tendon must be at least 70 mm².

Actually the Achilles cross section is around 120 mm² for a man of 80 kg body weight. This estimation shows that the safety factor for tendons is much smaller than for bone. Uncontrolled muscle contraction by an electrical shock can result in tendon rupture. To avoid tendon ruptures due to voluntary muscle contractions Golgi organs in the muscle-tendon interface act as strain gauges and switch off the muscle when a definite deformation is exceeded. This also explains that the maximum voluntary muscle force cannot (or only to a very small extent) be increased in adulthood by any training. The ability of bone to adapt to changes in the maximum muscle forces is limited by a feedback loop of the tendons that prevent ruptures from voluntary muscle contractions.