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LONGITUDINAL ARCH LOAD-SHARING SYSTEM OF THE FOOT

One of the most elegant design components of the human foot is its unique longitudinal arch. Leonardo Da Vinci, called the human foot "a masterpiece of engineering and a work of art". There are multiple drawings of the foot from Da Vinci's notebooks which seem to clearly indicate how this Renaissance painter, sculptor, architect and inventor appreciated both the structure and function of the longitudinal arch of the foot (Valderrabano V, Easley M (eds): *Foot and Ankle Sports Orthopaedics.* Springer, New York, 2016, p. 25)

In order to maintain stability and also allow flexibility of the longitudinal arch under varying loads and weightbearing activities, the longitudinal arch of the foot has four layers of tension load-bearing elements within its plantar structure which not only provides a baseline of longitudinal arch stiffness during less-demanding weightbearing activities, but also allows the central nervous system (CNS) to increase longitudinal arch stiffness during more strenuous weightbearing activities. These multiple layers of tension load-bearing elements interact mechanically with each other in what is known in engineering as a "load-sharing system".

Load-sharing is a commonly applied concept in both mechanical and electrical systems where redundancy of operation is vital to the reliability of the system as a whole. Examples of load-sharing systems include multiple engines in aircraft, multiple electric generators in power-generation systems, and the use of multiple supporting cables in suspension bridges. In a load-sharing system, each component of the system shares the load with each other component so that if one component fails, the system can still remain operational. However, if one of the components of the load-sharing system does fail, the loads now acting on the remaining components are increased (Ye Z, Revie M, Walls L: A load sharing system reliability model with managed component degradation. IEEE Transactions on Reliability. 63(3):721-730, 2014).

In 2012, the concept of the Longitudinal Arch Load-Sharing System (LALSS) of the Foot was first described within the medical literature (Kirby KA: March 2012 newsletter in: Kirby KA: Foot and Lower Extremity Biomechanics IV: Precision Intricast Newsletters, 2009-2013. Precision Intricast, Inc., Payson, AZ, 2014, pp. 31-32). The LALSS has four layers of tension load-bearing elements which not only provide a baseline stiffness to help resist arch-flattening loads during weightbearing activities but also functions to allow increased arch-stiffening under direct control of the CNS. In addition, the redundancy in longitudinal arch support which these four elements of the LALSS provide ensures that an individual with an injury to one or more of these elements will not experience total collapse of the arch, but will still have some longitudinal arch function during weightbearing activities (Kirby KA: Longitudinal arch load-sharing system of the foot. Revista Española de Podología, 28(2), 2017).

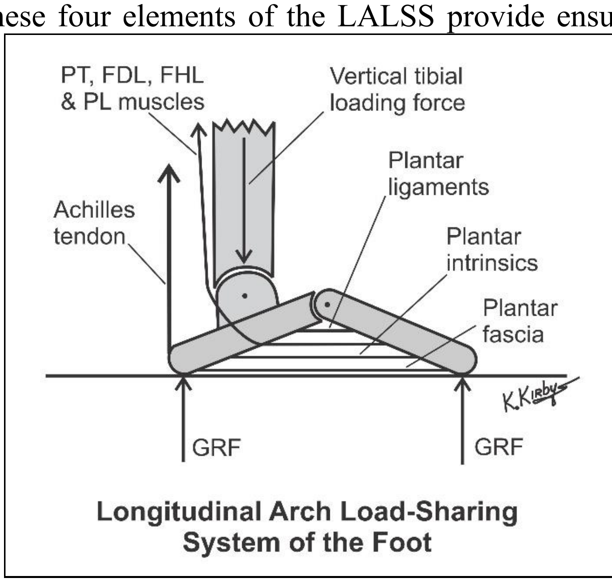

Figure 1. In the Longitudinal Arch Load-Sharing System of the Foot, four layers of both passively-controlled and actively-controlled tension load-bearing structures work synergistically to help stiffen the longitudinal arch and prevent longitudinal arch flattening during weightbearing activities.

The most superficial element of the LALSS is the plantar fascia (i.e., central component of the plantar aponeurosis). Since it contains no muscle fibers, the plantar fascia is not directly controlled by the CNS. Rather, plantar fascial tension is dependent on the lengthening and flattening of the longitudinal arch that occurs when ground reaction force (GRF) acts upon the plantar forefoot. An increase in GRF on the plantar forefoot will tend to both elongate and lower the longitudinal arch which, in turn, passively increases the plantar fascial tension and increases the stiffness of the longitudinal arch. In other words, the intact plantar fascia, by itself, has the ability to help prevent longitudinal arch flattening by having its tension increased with application of plantar forefoot GRF, thereby increasing longitudinal arch stiffness.

Just deep to the plantar fascia is the next tension load-bearing element of the LALSS, the plantar intrinsic muscles. The plantar intrinsic muscles, being under the control of the CNS, do have the ability to increase their tension forces independent of flattening of the longitudinal arch. In other words, the tension force within the plantar intrinsic muscles can be increased by increased efferent neural activity from the CNS which, in turn, allows the CNS to control the arch-flattening stiffness of the foot. In fact, research using fine-wire electromyography has shown that the plantar intrinsic muscles have multiple functions including the ability to stiffen the longitudinal arch which aids balance in unipedal and bipedal standing, to actually elevate the longitudinal arch height, and to have increased activity in faster walking, and especially during running activities to help stabilize the arch (Kelly LA et al.: Recruitment of the plantar intrinsic foot muscles with increasing postural demand. Clin Biomech, 27:46-51, 2012; Kelly LA et al.: Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch. J. R. Soc. Interface, 1193:20131188.1-20131188.9. doi:10.1098/rsif.2013.1188, 2014; Kelly LA et al.: Active regulation of longitudinal arch compression and recoil during walking and running. J.R. Soc. Interface, 12 102:1-8. doi:10.1098/rsif.2014.1076, 2014).

Deep to the plantar intrinsic muscles is the next element of the LALSS, the peroneus longus and deep flexor muscles (i.e., posterior tibial, flexor digitorum longus and flexor hallucis). Again, like the plantar intrinsic muscles, the contractile activity and tension within the tendons of these muscles is directly controlled by efferent activity from the CNS. The posterior tibial (PT) and peroneus longus (PL) tendons directly insert onto the bones of the plantar midfoot to create a plantarflexion moment of the forefoot on the rearfoot which, in turn, increases the longitudinal arch stiffness upon their contractile activity. However, the flexor digitorum longus (FDL) and flexor hallucis longus (FHL) tendons, by attaching to the digits distal to the metatarsophalangeal joints, create their forefoot plantarflexion moment and their increase in longitudinal arch stiffness by increasing posteriorly-directed force acting on the distal metatarsal heads.

The deepest element of the LALSS are the plantar ligaments which help prevent longitudinal arch flattening and increase the longitudinal arch stiffness by the tension forces they passively exert upon their attachments to the plantar aspects of the joints of the rearfoot and midfoot. Like the plantar fascia, the plantar ligaments can only act passively since their tension force is not directly controlled by the CNS. When combined with the ability of the plantar fascia to help stiffen the longitudinal arch and prevent excessive longitudinal arch flattening, the plantar ligaments and plantar fascia together provide a “baseline” longitudinal arch stiffness which is not under control of the CNS. In other words, even in a cadaver foot, with no muscle activity being possible within the plantar intrinsic and extrinsic muscles of the foot, the non-living foot can still maintain the height of its longitudinal arch even under significant weightbearing loads.

In summary, the passive non-CNS-controlled plantar fascia and plantar ligaments work synergistically with the active CNS-controlled plantar intrinsic muscles and the PT, FDL, FHL and PL muscles to provide a baseline of longitudinal arch height and stiffness and, also, the CNS can vary the magnitude and temporal patterns of arch stiffness as activities demand. In this fashion, the active LALSS tension load-bearing elements can adjust medial and/or lateral longitudinal arch stiffness so that the magnitude and plantar location of GRF can be altered at any instant during gait or during any other weightbearing activity. Since all four elements of the LALSS have the ability to exert significant tension forces on the osseous structures which they attach to within the plantar arch of the foot, all four components of the LALSS work separately and together to increase the overall stiffness of the longitudinal arch of the foot. Much like the microprocessor-controlled shock absorbers of an advanced motor vehicle rear-suspension system that optimizes driving comfort, efficiency and safety over a variety of surfaces and speeds, the LALSS with its passive and active CNS-controlled tension load-bearing elements, provides the bipedal human with the ability to perform their daily weightbearing activities more smoothly, efficiently and with reduced risk of injury (Kirby KA, 2017).

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