

Rationale for the Hypodense Calcaneal Region of Ward's Neutral Triangle

ABSTRACT

The calcaneus, more commonly known as the heel bone, is the most fractured tarsal bone. The vast majority of calcaneus fracture lines propagate through a hypodense region of bone called Ward's neutral triangle. The presence of this region of sparse trabecular bone is best explained through close analysis of the evolution of bipedalism. Certain species that necessitate falls from height to survive have a foot anatomy that effectively sustains the force of such falls. Humans, however, have evolved in such a way that axial loading mechanisms, such as falling from height, are not necessary for survival. Consequently, the human foot has evolved accordingly. Ward's neutral triangle is simply a manifestation of this process. This study seeks to elucidate the presence of Ward's neutral triangle as a consequence of bipedal evolution.

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Calcaneal fractures account for 2% of all fractures and 60% of all tarsal fractures.¹ Approximately 75% of calcaneus fractures are intra-articular and occur from an axial-load mechanism¹ often resulting from a fall from height or motor vehicle accident. In general, supraphysiologic axial loading on the foot generates a primary fracture line that propagates near the angle of Gissane and exits the calcaneus plantarly. Secondary fracture lines are created that extend to the tuberosity resulting in either a tongue-type pattern, where the posterior facet remains in continuity with the tuber, or a joint-depression fracture where the posterior facet is separated. The primary fracture line in intra-articular calcaneus fractures consistently travels through an area known as Ward's neutral triangle, which underlies the posterior facet (**Figure 1A**). This neutral triangle is a region of the calcaneus with sparse mineralization and a relative hypodensity of trabecular bone which is particularly susceptible to fractures from axial loading mechanisms (**Figure 1B**). As the posterior facet of the calcaneus bears approximately 70% of axial load forces transmitted through the talus, it seems disadvantageous from an evolutionary point of view to have an area of hypodensity directly inferior to the posterior facet and seemingly counter-intuitive to Wolff's law. Simply put, the question arises why we have very little trabecular bone in the area of the calcaneus which seems to require it the most. An explanation may be found through examination of the evolution of bipedalism and function of the foot when compared to other quadrupeds.

It is generally accepted that the evolution of bipedal locomotion was one of the most significant adaptations to occur. Bipedalism is what separated the first hominids from the rest of the four-legged apes.² Of all extant primates, humans are the only obligate bipeds.² The reasons as to why bipedalism evolved remains to be concretely elucidated. While multiple theories exist, one claim argues that bipedalism evolved as a consequence of ecological changes in Africa that progressively required the use of free arms to gather food.² Another argument revolves around the idea of efficiency of bipedalism, and that natural selection favored the development of upright walking.² Regardless, the development of bipedalism propagated crucial changes in both the function and anatomy of the foot.

The human foot is particularly specialized, both anatomically and functionally. In the evolution of bipedal locomotion, the foot was the only structure that directly connected with the ground, and was therefore under strong selective pressures to efficiently handle both balance and propulsion. Furthermore, since only the lower limbs are used for

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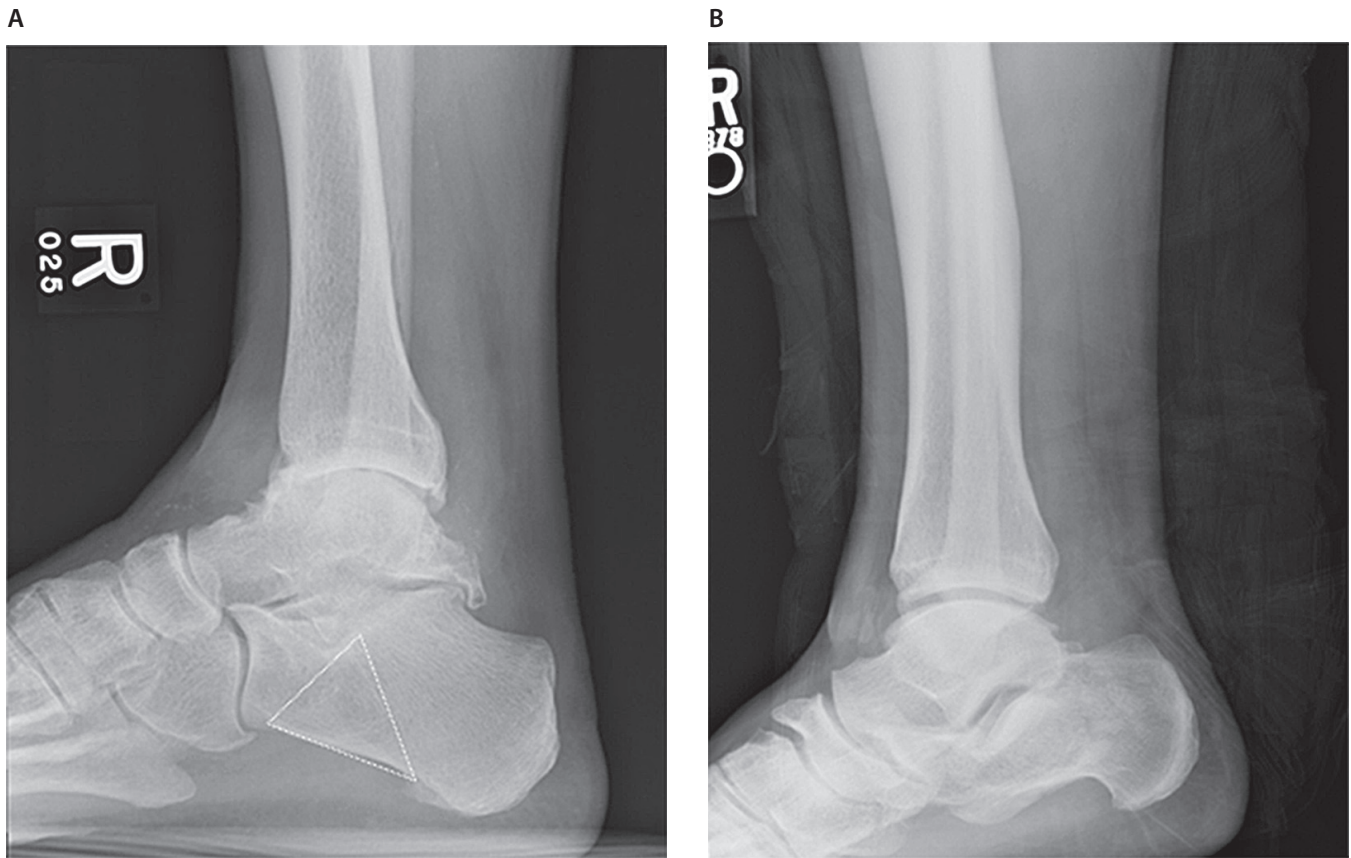
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FIGURE 1 Axial loading is common mechanism for fractures of the calcaneus

(A) The neutral triangle is a region of the calcaneus with sparse mineralization and a relative hypodensity of trabecular bone (white dotted region). (B) This triangular window is particularly susceptible to fractures from axial loading mechanisms, as represented in this individual who suffered a calcaneus fracture due to fall.

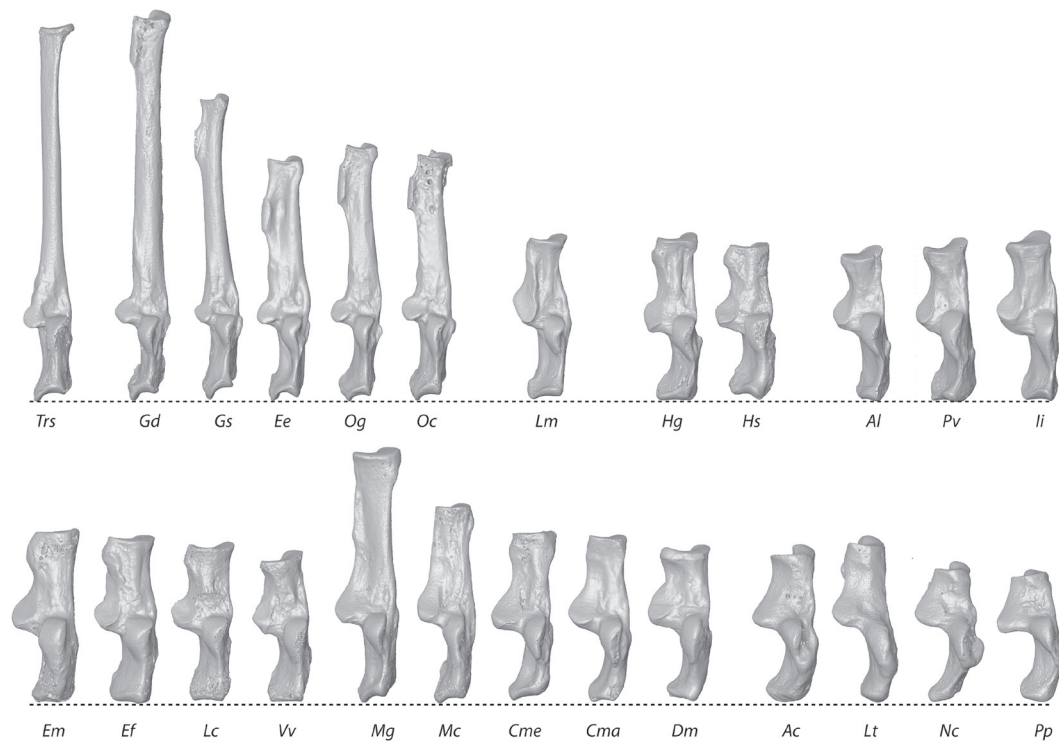
propulsion, the body's entire weight passes through one foot at a time as the biped moves between swing and stance phases of locomotion. This has important implications for the anatomy of the foot. The calcaneus, for instance, is comparatively more robust in humans than in chimpanzees.² Its robust size helps to provide stability and absorb the high forces encountered during heel strike, and progressive evolutionary changes of the size and shape of the calcaneus can be seen in fossil hominins (**Figure 2**). Furthermore the shape of the calcaneus provides for the attachment of strong ligaments that run from the arch of the foot to the tibia. These ligaments add support, creating a double arch system that helps to absorb the forces as the foot hits the ground. Thus, the anatomical changes in the calcaneus of bipeds certainly have a pragmatic functionality.

Another notable difference in bipedal species is that the first metatarsal is notably larger than the other metatarsals and is also fully adducted (commonly known as the non-opposable hallux). Compared to other primates, human phalanges are relatively short and lack the grasping function seen in other primates. Evolutionarily speaking, walking bipedally with longer toes and a

divergent opposable-hallux would have limited efficient bipedalism due to being relatively energetically demanding. As such, toe length and a non-opposable hallux are adaptations for habitual and efficient bipedalism.

The highest impact on the calcaneus during normal human function is at heel strike. Consequently, the various compressive and tensile trabeculae are arranged in such a way that this force is sustained. A dominant compressive trabecular pattern running obliquely from antero-posterior along the long axis of the calcaneus can be observed. In the posterior tuberosity, the trabeculae are arranged parallel to the posterior border. The thickest sites of the calcaneal cortex are the lower pole of the posterior tuberosity, the upper surface at the angle of Gissane, and the lateral surface below the anterior portion of the posterior facet. The thinnest site is the neutral triangle where there is a relative lack of compressive trabeculae (**Figure 3**).

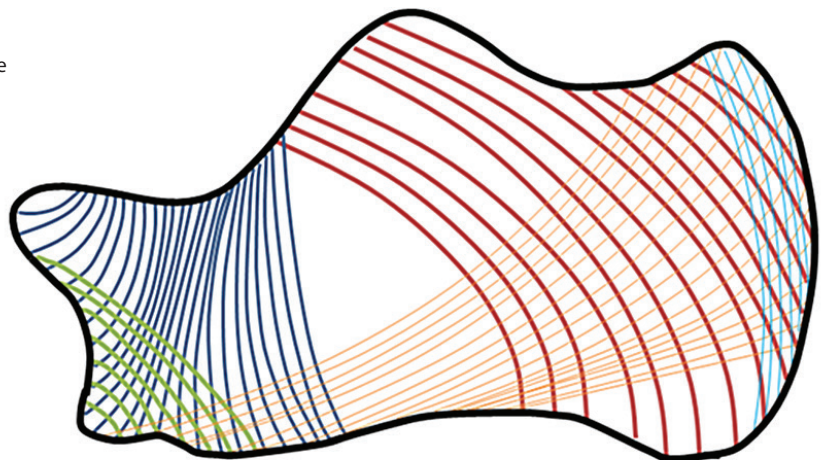
Unlike quadrupeds, necessary human activity does not typically involve falling or jumping from heights. As such, the anatomy of the human foot is not designed in such a way that the force of a fall can be sustained. Instead, the human foot

FIGURE 2 A comparison of calcaneal geometry amongst prosimians


Scaled to length at the proximal segment, and arranged within familial groups, the same taxa are represented. It is important to note the allometric differences amongst calcanei as it relates to niche functionality of species. Abbreviations are as follows: Abbreviations: Ac, *Arctocebus calabarensis*; Al, *Avahi laniger*; Cma, *Cheirogaleus major*; Cme, *Cheirogaleus medius*; Dm, *Daubentonia madagascariensis*; Ee, *Euoticus elegantulus*; Ef, *Eulemur fulvus*; Em, *Eulemur mongoz*; Gd, *Galagoides demidovii*; Gs, *Galago senegalensis*; Hg, *Hapalemur griseus*; Hs, *Hapalemur simus*; li, *Indri indri*; Lc, *Lemur catta*; Lm, *Lepilemur mustelinus*; Lt, *Loris tardigradus*; Mc, *Mirza coquereli*; Mg, *Microcebus griseorufus*; Nc, *Nycticebus coucang*; Oc, *Otolemur crassicaudatus*; Og, *Otolemur garnetti*; Pp, *Perodicticus potto*; Pv, *Propithecus verreauxi*; Vv, *Varecia variegata*. **Original figure from Boyer et al.¹⁶**

FIGURE 3 Trabecular pattern of the calcaneus

- Thalamic: Primary Compressive Trabeculae
- Anterior apophyseal: Secondary Compressive Trabeculae
- Inferior plantar: Primary Tensile Trabeculae
- Anterior plantar: Secondary Tensile Trabeculae
- Posterior achillean: Tendotuberosity (Tensile)



The normal calcaneus trabecular architecture encompasses is characterized by five trabecular groups (two compressive and three tensile). A triangular region confined superiorly by the primary and secondary compressive trabeculae and inferiorly by the tensile trabeculae is referred to as the foramen calcaneus or Ward's triangle.

is designed to bear the weight necessary for effective human locomotion and has evolved accordingly. In other words, the anatomy of the foot, specifically the neutral triangle, reflects that falling or jumping from height is a supraphysiologic activity that we simply were not designed to do. For this reason, axial loading, a mechanism for which humans are not adapted, generally results in a primary fracture line through the hypodense neutral triangle.

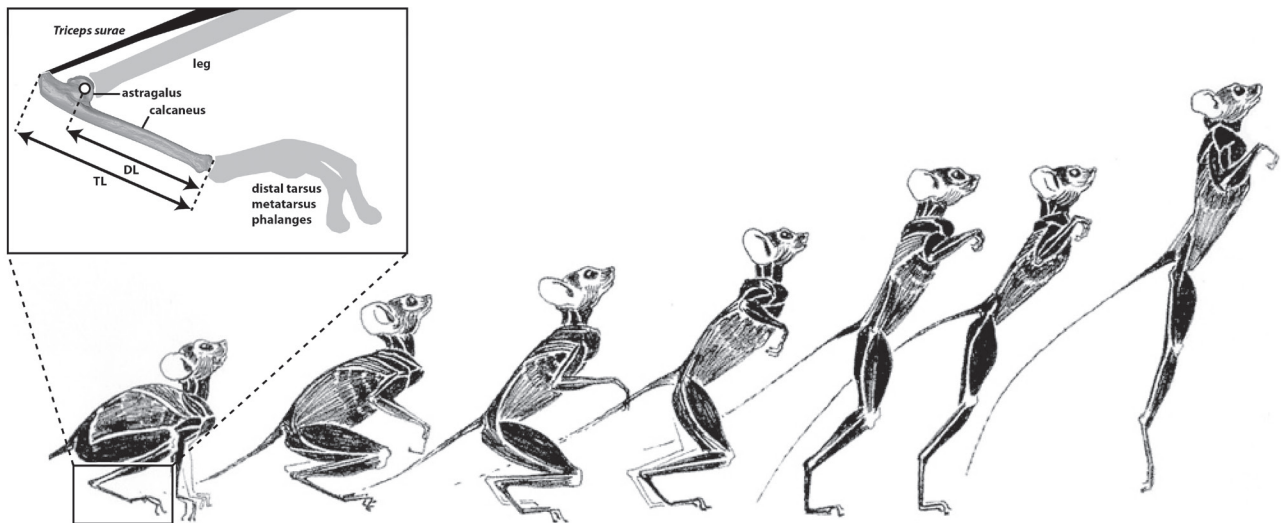
Comparatively speaking, there are various evolutionary adaptations that allow quadrupeds to sustain little to no injury from falls that would otherwise lead to severe orthopaedic trauma or death in humans. Many quadrupeds have long, muscular legs adapted for climbing trees. Upon falling or jumping from a height, the four legs essentially act as shock absorbers. The force absorbed is spread among four legs, as opposed to two, thus decreasing the potential damage to each limb. Interestingly, the large muscles allow quadrupeds to divert high energy into deceleration once they hit the ground thus reducing the impact of the collision. It is no surprise that many allometric differences exist between humans and quadrupeds due to unique physical and behavioral demands. Among smaller quadrupedal taxa, an elongated distal segment of the calcaneus has been theorized to reflect a proclivity for acrobatic leaping^{3,4} or with a specialized niche of vertical clinging and leaping.⁵ This is particularly evident in lemurs (**Figure 4**). Although there is debate regarding some morphological correlations of grasp-leaping,⁶ such

behaviors are often implicated as a determinant in the early adaptive radiation of euprimates.⁷⁻⁹ As simple biomechanical lever systems, musculoskeletal architecture defines the behavioral capabilities of vertebrates. Longer bones allow for longer moment arms created by muscle attachments, which catalyze a maximum force capacity along the parallel axis of moment arm or bone. Light-weight or notably large muscles potentiate the ultimate capacity of acceleration – the key ingredient in leaping, effective hunting, and sprinting.

Consequently, many quadrupeds, namely cats, have been known to survive from falls with significantly less orthopaedic trauma than would be seen in humans. Just recently, a cat in Boston survived a 19-story fall with very little injury.¹⁰ In a 1987 study of 132 cats brought to a New York City emergency veterinary clinic after falls from high-rise buildings, 90% of treated cats survived.¹¹ The median lethal dose (LD50) for humans for falls is 4 stories, or 48 feet.¹² Cats, however, are often seen surviving falls from 20-30 stories.

Had we been designed to fall, perhaps the neutral triangle would not have existed. The anatomy of the foot and leg would be vastly different, similar to that of a quadruped's. However, the evolution of bipedalism caused immense alterations to the anatomy of the foot, and with those alterations came physical limitations to what humans are capable of performing and enduring.

FIGURE 4 Biomechanics of elongated distal segment of calcaneus in lemurs during leaping



Among smaller quadrupedal taxa, an elongated distal segment of the calcaneus has been theorized to reflect a proclivity for acrobatic leaping or with a specialized niche of vertical clinging and leaping. **Original figure from Boyer et al.¹⁶**

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