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BIO-complexity

Critical Focus

# Why the Ankle-Foot Complex Is a Masterpiece of Engineering and a Rebuttal of "Bad Design" Arguments

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## Abstract

To perform agile bipedal movement, human feet must meet extremely demanding requirements in terms of compactness, flexibility, strength, joint movements, actuation, and control. These requirements are met through very sophisticated engineering solutions. This paper describes four highly specialised mechanical features of the ankle-foot complex that show a very high degree of complexity and fine-tuning: i) a multi-arched structure; ii) a multifunctioning midfoot; iii) elastic hinge joints; and iv) a fibula linkage mechanism. Engineering insight reveals a close relationship between form and function in the ankle, a relationship seen in its multiple bones and the layout of those bones. In particular, it is shown that the five midfoot bones are needed to form the optimal kinematic and structural interface between the hindfoot and forefoot. The relatively poor performance of prosthetic feet, robot feet, and replacement ankles confirms that bipedal movement involves extremely demanding requirements and that the human foot is an example of masterful engineering. The claims of bad design in human feet by authors such as Nathan Lents are shown to clearly contradict scientific evidence.


**Cite as:** Burgess S (2022) Why the ankle-foot complex is a masterpiece of engineering and a rebuttal of bad design arguments. BIO-Complexity 2022(2):1–10. **doi:**10.5048/BIO-C.2022.3.

**Editor:** Robert J. Marks II

**Received:** May 26, 2022; **Accepted:** July 11, 2022; **Published:** November 28, 2022



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## INTRODUCTION

The human foot is generally split into three anatomical sections: hindfoot, midfoot, and forefoot. In this paper the ankle-foot complex is defined as the seven bones of the hindfoot and midfoot, together with the fibula, as shown in Figure 1. Whilst the main joint of the ankle is between the lower leg bones (tibia/fibula) and the foot, there is also a lower ankle joint between the two bones in the hindfoot. Since the two ankle joints work closely together with the joints in the midfoot, it is common to consider the hindfoot and midfoot together when considering the functions of the ankle. The ankle-foot complex is also stabilised by the fibula, so there are actually eight bones that need to be considered when analysing the performance of the ankle.

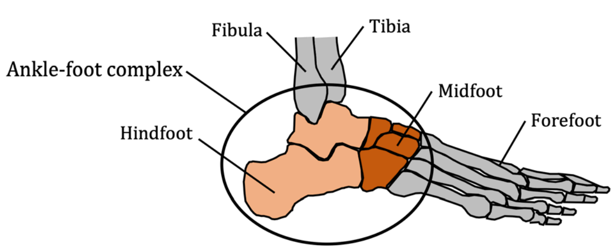



**Figure 1: The ankle-foot complex. doi:**10.5048/BIO-C.2022.3.f1

The foot is a compact multifunctioning device. The main functions of the ankle-foot complex can be summarised as shown in Table 1 together with example applications.

**Table 1: Main functions of the foot**

| Function | Example applications |
|---|---|
| 1 Flexibility | Shock absorption and controlled push-off |
| 2 Strength and rigidity | Supporting the body in standing, walking and running |
| 3 Plantar-dorsiflexion | Joint movement for walking, running and jumping |
| 4 Pronation-supination | Joint movement for inward/outward rolling of ankle |
| 5 Balance | Two-legged and one-legged standing |

### Contrasting views on the quality of design of the ankle-foot complex

There are two contrasting views on the quality of the design of the human ankle-foot complex: the "excellent design" view and the "bad design" view.

*The "excellent design" view.* The traditional view from biomechanics teaching and research is that the ankle-foot complex represents an excellent design and that all seven bones and fibula have important functions. Just over 500 years ago, the great engineer and artist Leonardo da Vinci stated: "The foot is a masterpiece of engineering and a work of art" [1]. Leonardo made this statement based on his accurate anatomical observations and his expertise in engineering.

Researchers in bioinspired design have reported on the fine-tuning in human feet that maximises efficiency of locomotion [2]. Researchers in sports biomechanics have described how the combination of stiffness and flexibility of the human foot gives "nearly effortless human gait" [3]. In a review of the biomechanics of the ankle joint, researchers described the ankle as having a high degree of stability and robustness despite very high loading [4]. An established biomechanics textbook states that the structures of the foot "work in perfect synchronisation" [5]. A medical educational website describes the foot as "superbly constructed for ambulation" [6].

Journal publications in biomechanics support the view that each of the individual bones of the ankle-foot complex has important functions [7–8]. One popular biomechanics resource explains the importance of the individual joints in the midfoot for producing flexibility in the joint [9]. The very important role of the fibula for stabilising the ankle-foot complex has been reported by several researchers [10–12].

*The "bad design" view.* A second view on the quality of design of the ankle-foot complex, which is based on evolutionary reasoning, is that it is a bad design. The "bad design" view of the ankle has recently been argued by Nathan Lents in his book *Human Errors* [13]. Lents makes the following five criticisms of the design of the ankle joint:

1. The ankle contains seven bones, most of them pointless (see [13], p. 29 and front cover).
2. There is no real reason to have paired bones [in the lower leg] (see [13], p. 31).
3. Because many of the bones of the ankle do not move relative to one another, they would function better as a single, fused structure, their ligaments replaced with solid bone (see [13], p. 29).
4. [The reason] sprain ankles are so common… [is that] the ankle is a hodgepodge of parts that can do nothing but malfunction (see [13], p. 29).
5. No engineer would design a joint with so many separate parts (see [13], p. 29).

Lents makes his claims based on two assumptions: (i) that humans have evolved from a four-legged, ape-like creature; and (ii) the requirements for bipedal motion are so different from quadrupedal motion that evolution would not be able to produce a highly optimised design. In particular, Lents states that evolution would be limited in its ability to delete functionless bones [13]. Lents essentially argues that since evolution could not produce an optimal layout of bones in the ankle-foot complex, the ankle-foot complex must therefore be assumed to be a very sub-optimal design.

Another proponent of the bad design argument, using evolutionary assumptions, is Jeremy DeSilva [14]. Like Lents, DeSilva essentially argues that evolution would not be able to evolve an optimal lever structure from a grasping structure and therefore the human foot must be assumed to be a bad design.

### Using engineering insight to assess quality of design

The arguments of bad design described above are based on circular reasoning and assumptions about what evolution could or could not do in the past. A better scientific approach to assessing the quality of design is to study the actual biomechanics and functions of the foot. We describe the anatomy of the ankle-foot complex in Section 2 and the requirements of bipedal movement in Section 3; in Sections 4–7 we describe four specialised features of the ankle-foot complex that show a very high degree of complexity and fine-tuning. These specialised features show that the foot represents not just excellent design but a masterpiece of engineering. In Section 8 we give detailed responses to claims of bad design.

## ANATOMY OF THE ANKLE-FOOT JOINT COMPLEX

The seven bones of the ankle-foot complex are shown in Figure 2. The ankle-foot complex is capable of movement in three perpendicular planes, as shown in Figure 2. Flexion (plantarflexion-dorsiflexion) occurs around the x-axis, abduction-adduction occurs around the z-axis and eversion-inversion

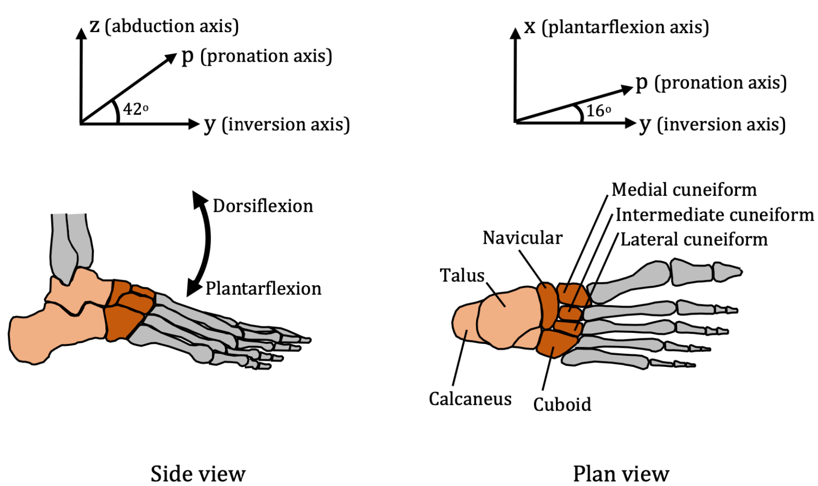
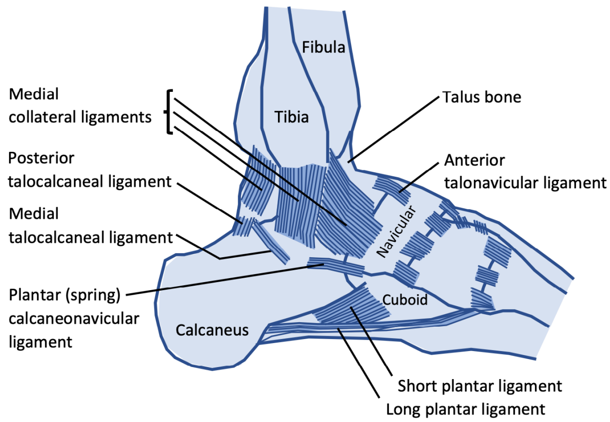
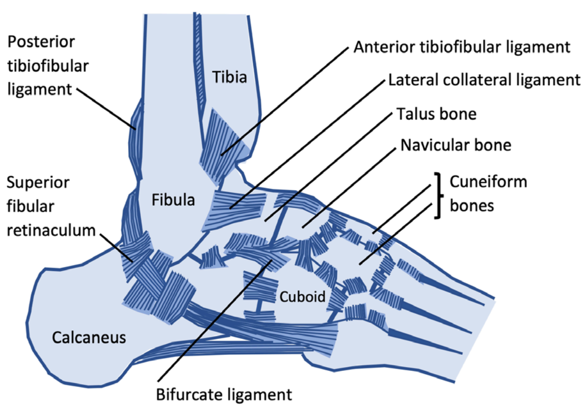


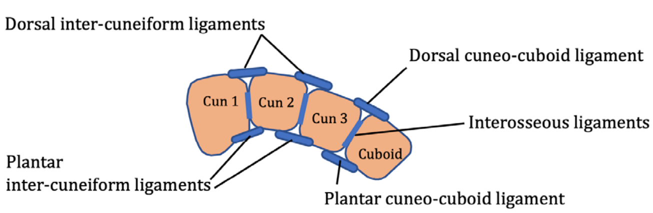

**Figure 2: Two views of the ankle-foot complex.** **doi:**10.5048/BIO-C.2022.3.f2




**Medial (inside) view of ankle-foot complex showing the main ligaments**




**Lateral (outside) view of ankle-foot complex showing the main ligaments**




**Ligaments of the transverse arch in the midfoot**

**Figure 3: Main ligaments of the ankle-foot complex.** **doi:**10.5048/BIO-C.2022.3.f3

occurs around the y-axis (Figure 2). However, the ankle joint as a whole is often described as having two main joint movements, typically defined as plantarflexion-dorsiflexion and pronation-supination [5]. Pronation-supination occurs around the p-axis [15] which has an angled orientation as shown in Figure 2. Pronation involves a combination of eversion, abduction and dorsiflexion whilst supination involves a combination of inversion, adduction and plantarflexion.

The seven bones of the ankle-foot complex are held tightly together by numerous ligaments, as shown in Figure 3. There are approximately 50 ligaments and 10 muscles associated with the ankle-foot complex [16]. The arched structure of human feet is unique amongst mammals. The forward-pointing big toe is also unique. In contrast, apes have grasping (prehensile) feet like hands with a sideways-facing big toe which is ideal for four-legged walking and tree climbing.

## REQUIREMENTS FOR AGILE BIPEDAL MOVEMENT

The requirements for agile bipedal movement are extremely demanding. The foot must be a compact multifunctioning precision device, fulfilling the following requirements:

1. *Act as a strong and stiff lever* [Figure 4(a)] to propel the body forwards in walking and running. Joint movement is plantarflexion.
2. *Act as a flexible platform* [Figure 4(b)] to absorb shocks and adapt to uneven ground. Joint movements include dorsi-flexion, pronation, and supination.
3. *Provide 3-point contact with the ground* [Figures 4(c) and 4(d)] to allow standing on one or two legs and to enable controlled push-off from the ball of the feet. The control must involve fine adjustment of direction as well as power.

The requirements of a stiff lever and flexible platform are difficult to achieve because they are contradictory. To achieve these two requirements the foot must have stiffness and flexibility in just the right places. In addition, the foot must have the ability to adjust stiffness through precise control of muscles.

Three-point contact with the ground enables two-legged standing to be carried out with relative ease because the centre of gravity of the body can be placed within a relatively large

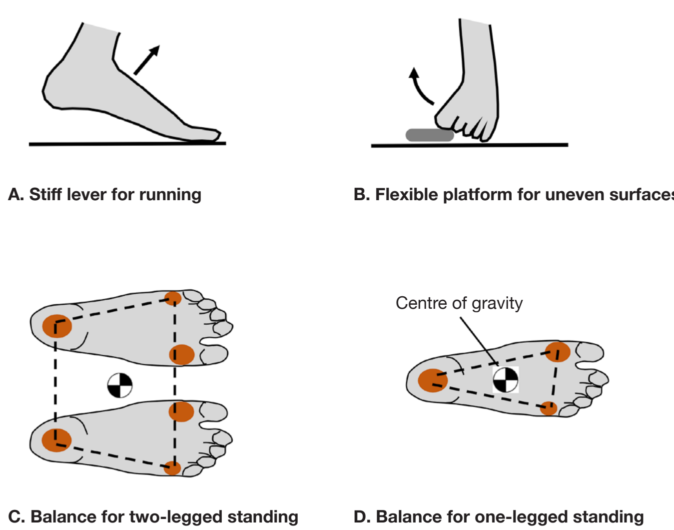



**Figure 4: Requirements for agile bipedal standing, walking and running.** **doi:**10.5048/BIO-C.2022.3.f4

trapezium area, as shown in Figure 4(c). However, in the case of one-legged standing, the centre of gravity must be placed within a small triangle [Figure 4(d)]. In the case of running, a change of direction is achieved by placing the centre of gravity outside of the triangle in a precise and controlled way. Having two contact points spaced far apart at the front of the foot is important to maximise control of balance and movement. The unique human ability to push off the ball of the feet in different directions can be appreciated by studying the movement of feet in a sport like basketball or tennis.

## SPECIALISED MULTI-ARCHED STRUCTURE

To fulfil the requirements for agile bipedal motion, the foot has three interconnecting flexible arches that perform multiple functions in particular three-point contact with the ground, stiff lever for take-off and flexibility for shock absorption. The functions and features of these arches are summarised in Figure 5. All three arches are able to bend and flatten to absorb shocks and also store and release energy. There are also specific functions for each arch.

### Medial arch

The medial arch is very stiff with a very stiff big toe which points forwards. This makes it an ideal arch for pushing-off during walking and running. The medial arch is also strongly connected to the leg via the talus bone so that the power of the leg muscles is focused on the medial arch. It can be seen in Figure 5 how the talus aligns exactly with the navicular bone in the medial arch.

### Lateral arch

The lateral arch forms the other ground contact point at the ball of the little toe, thus maximising the distance between the two front points of contact. The lower height and the lower stiffness of the lateral arch produce a lower pressure when landing on the ground. This is why the human body has a natural running style that involves landing on the outside of the foot.

### Transverse arch

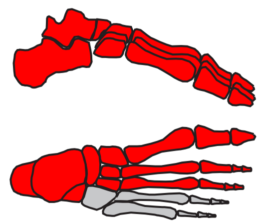
The transverse arch is formed by the three cuneiform bones and cuboid bone in the midfoot as well as the bases of the metatarsal bones, as shown in Figure 5. The transverse arch helps transmit loads from the lateral arch to the medial arch during pronation when the foot rolls from the outside of the foot to the inside.

### Design features of the arches

There are several features that maintain the integrity of the arches [17]: (i) foot arches segmented like a Roman arch [15], which induces compressive forces, particularly the bone that forms the keystone to the arch; (ii) short ligaments that tie adjacent bones together; (iii) longer ligaments (like the spring ligament) that tie the arch across multiple bones; (iv) muscle-tendon groups that act like a sling, pulling the arches upwards; and (v) muscles that stiffen the arch.

**Arch** | **Functions and features**

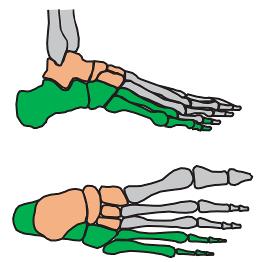
**Medial longitudinal arch**



**Main functions:**
- Stiff lever for push-off
- Contributes to 3-point contact

**Design features:**
- Stiff big toe pointing forwards
- Two contact points with ground (Calcaneus and ball of big toe)
- Talus keystone
- Spring ligament (connects calcaneus to navicular)

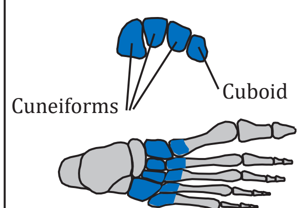
**Lateral longitudinal arch**



**Main functions:**
- Low flexible arch for landing
- Contributes to 3-point contact

**Design features:**
- Two contact points with ground (Calcaneus and ball of little toe)
- Cuboid keystone

**Transverse arch**




**Main functions:**
- Flexible arch

**Design features:**
- Cuboid needed to differentiate medial and lateral arches
- Intermediate cuneiform keystone

* some researchers recognise an additional anterior transverse arch at the heads of the metatarsals [17].

**Figure 5: Arches of the foot.** Note that some researchers recognize an additional anterior transverse arch at the heads of the metatarsals [17]. **doi:**10.5048/BIO-C.2022.3.f5

## SPECIALISED MULTIFUNCTIONING MIDFOOT

The midfoot is a small part of the foot, yet it is a truly remarkable multifunctioning assembly. It includes the following five main sub-functions:

### Sub-function 1: Flexible transverse arch

As explained in Section 4, the three cuneiform bones and cuboid bone are the main components of a flexible arch which acts as a shock absorber and energy storage system.

### Sub-function 2: Load bearing structure during pronation

As explained in Section 4, the transverse arch helps transmit loads from the lateral arch to the medial arch during pronation.

### Sub-function 3: Kinematic interfaces for pronation-supination

Pronation occurs when the foot rolls inwards after the foot lands during running, whilst supination involves the foot rolling outwards. During pronation, there is a twisting action between the forefoot and hindfoot, as shown in Figure 6. This twisting action can be large when walking or running on uneven ground. Pronation-supination mainly takes place at the talocalcaneonavicular joint (between the talus, calcaneus and navicular) [18].

The midfoot performs the complex task of providing a kinematic interface that smoothly accommodates pronation-supination. The talocalcaneonavicular joint forms a ball and socket joint [19]. In addition, the most significant movement occurs at the talonavicular joint [20]. Such a joint is only possible if the midfoot contains the navicular bone in front of the three cuneiforms. This is necessary because a ball and socket joint only works efficiently if the ball is one bone and the socket is one bone. On the other hand, the first three metatarsal bones in the forefoot require three individual joints in the midfoot which are provided by the three cuneiforms. Therefore, the kinematic interface function explains the rationale for having the navicular bone in front of the three cuneiforms.

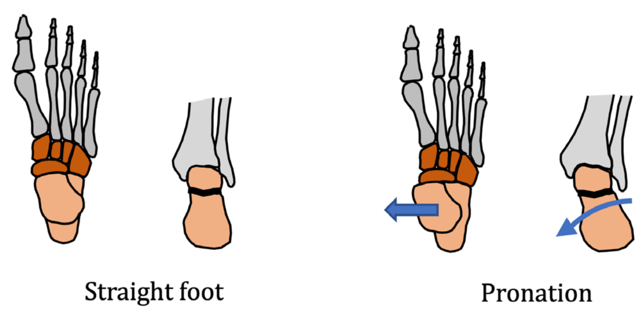



**Figure 6: Movement between forefoot and hindfoot during pronation.** doi:10.5048/BIO-C.2022.3.f6

### Sub-function 4: Structural interface for longitudinal loads

The four-bone layout of the midfoot transverse arch (three cuneiforms and cuboid) is optimal for horizontal loading because it helps to create compression load paths from the toes in the forefoot to the bones in the hindfoot. Figure 7 shows how the three cuneiforms line up exactly with the three big toes. This minimises shear and bending loads in the midfoot area. Shear and bending loads are structurally inefficient partly because bending loads magnify forces and partly because materials like bone are strong in compression but relatively weak in tension and shear. The fact that the cuboid bone receives loads from the two smallest toes does not significantly hinder the compression load paths because the loads are significantly lower in these two toes. It can be noted that research has shown that the second and third toes tend to form one column [15].

As explained in Section 4, the talus lines up with the navicular so that during push-off power is directed to the medial arch.

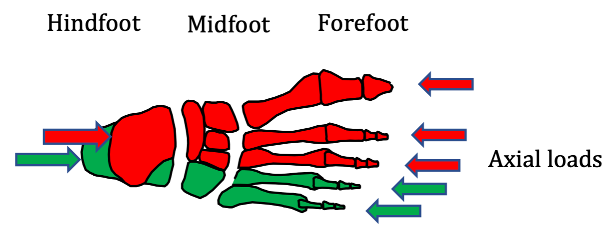



**Figure 7: Axial load paths through the foot.** doi:10.5048/BIO-C.2022.3.f6

In contrast, when landing on the lateral arch, the forces are not transferred directly through the talus and into the leg, thus reducing shock loads.

### Sub-function 5: Stiffening of the medial arch

Despite having a flexibility function (in its own plane), the transverse arch also has a stiffness function in the plane of the medial arch. Recent studies have estimated that the transverse arch contributes over 40% of the stiffness of the medial arch [21]. The stiffening effect of the transverse arch can be illustrated by analogy with a sheet of cardboard. When the cardboard is flat it is easy to bend. However, when it is curved in the transverse direction to the direction of bending, the card becomes much stiffer. The transverse arch is an example of how the foot has both flexibility and stiffness functions.

## SPECIALISED ELASTIC HINGE JOINTS

Another specialised design feature in the ankle-foot complex is the elastic hinge joints. Flexibility in each joint comes mainly from the elastic ligaments, although the tendons and muscles also play a role [22]. Even though the movement at one joint may be small, the large number of joints in the ankle-foot complex results in significant flexibility. There are approximately 17 joints associated with the ankle-foot complex [16].

Significant flexibility is needed for large joint movements of plantarflexion (40–55°) and dorsiflexion (10–20°) [4]. Flexibility is also needed between the hindfoot and midfoot for pronation-supination. However, flexibility is also needed between each of the bones in order to make the arches flexible for shock absorption [9].

### Model of elastic hinge joints

Whilst the Roman arch analogy is good for illustrating compressive forces in the foot, it is not adequate for modelling flexibility because a Roman arch cannot withstand significant displacements in the vertical or horizontal direction. To model the function of the joints, it is necessary to model how the arch forms elastic hinges.

Figure 8(a) gives an example of how elastic hinges are formed in the transverse arch. It can be noticed how a downward load $P$ causes the bottom ligaments to stretch, which in turn causes the bones to form hinges. For example, a stretch of $x$ at the bottom left ligament causes a hinge between the adjacent bones with an opening angle of $q$. It can also be seen how the horizontal stretch of ligaments causes a vertical deflection of $y$.

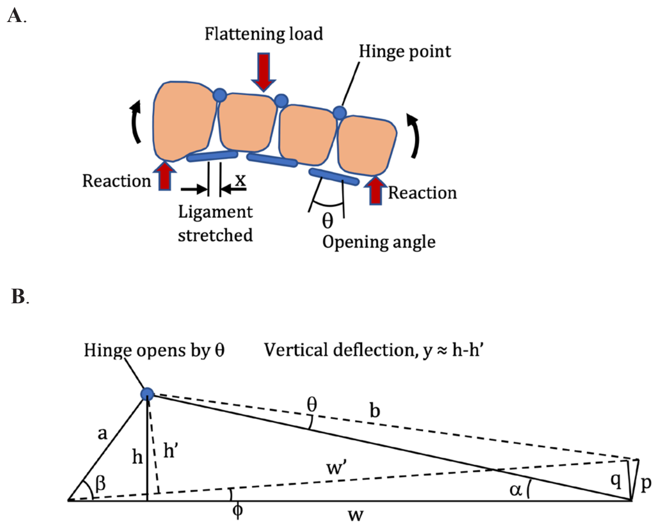



**Figure 8: Hinge model of transverse arch.** A. Transverse arch flattened under load. B. How a hinge rotation θ causes a vertical displacement, y. **doi:**10.5048/BIO-C.2022.3.f8

The presence of the flexible ligaments causes the vertical stiffness ($k_{vert} = P/y$) to reduce very significantly. The vertical stiffness of the arches is a function of the stiffness of the ligaments as well as the number of joints and the geometry of the arch. Figure 8(b) shows schematically how a hinge rotation $q$ at one hinge causes a change of geometry of the arch leading to a vertical deflection of $y$. This geometry in Figure 7(b) can be solved to calculate the vertical stiffness.

## Sub-functions of the elastic hinge joints

The elastic hinge joints have several sub-functions including: (i) flexibility; (ii) load-bearing; (iii) energy storage; (iv) fail-safe design; and (v) ultra-low friction. To illustrate the optimal performance of ligaments, Table 2 shows the key material properties for the first four sub-functions for ligaments and bone. The table shows how ligaments have superior material properties and performance factors to bone for the five sub-functions.

*Sub-function 1: Flexibility*. The ligaments of the foot have a material stiffness (E) approximately one-twentieth of that of bone, as shown in Table 2. This lower material stiffness is the most important reason for the flexibility of the arches. If the arches were made from solid bone, the stiffness would be around an order of magnitude higher compared to arches with elastic hinges, which would result in damaging shock loads on the foot.

*Sub-function 2: Load-bearing*. The superior tensile strength of ligaments is an important advantage because the human foot must be able to transfer large loads. In one study, the force in the Achilles tendon was found to be over eight times the body weight [28]. For an adult male weighing 70kg that corresponds to over half a tonne of force on the ankle joint.

Having separate bones and ligament joints ensures that the bones take mainly compression loads and the ligaments take the bulk of tension loads. This is optimal, because bone is strong in compression but relatively weak in tension. In one study, the strength of human cortical bone was measured to be around four times stronger in compression than tension [25]. In contrast, the tensile strength of ligaments has been measured to be up to five times stronger than the tensile strength of bone [23].

*Sub-function 3: Energy storage*. During running, ligaments can store energy (during landing) and release energy (during take-off) to improve the efficiency of running. For example, the medial arch has a spring ligament which is so-called because of its significant elastic property. The energy storage capacity is a function of three material properties [29], as shown in Table 2, with a higher index being best. The energy storage capacity is far greater for ligaments compared to bone, as shown in Table 2. This means that the presence of ligaments greatly improves the efficiency of running.

*Sub-function 4: Fail-safe design*. The ligament joints represent a fail-safe design because, when overloaded, they generally overstretch rather than fail completely. Even though the overstretching represents a significant injury, the ligaments can usually recover. In contrast, bone cannot tolerate much strain and is therefore more likely to form a complete fracture. The failure strain of ligaments [26] has been measured to be around eight times higher than that of bone [27], as shown in Table 2. Research has also shown that the foot is robust and has significant weight-bearing ability even after significant injury to an individual tendon or muscle [30]. Research has also shown that the ligaments are extremely tough [31], allowing repeated stretching over decades of use.

*Sub-function 5: Ultra-low friction*. To achieve extreme endurance (for 80+ years of use) it is necessary to have ultra-low

**Table 2: Material properties of ligaments and bone**

| Function | Design goal | Ligament | Bone |
|---|---|---|---|
| Flexibility | Maximise (low E) | E≈1.5 GPa [23] | $E_{bone}$≈30 GPa [24] |
| Tensile load bearing | Maximise | $s_{Ten}$≈150 MPa [23] | $s_{Ten}$ ≈30 MPa [25] |
| Energy storage performance index | Maximise | $\frac{\sigma_{Ten}^2}{E\rho} \approx 15$ | $\frac{\sigma_{Ten}^2}{E\rho} \approx 0.016$ |
| Failure strain | Maximise | ≈8% [26] | ≈1.1% [27] |

Key: E = Young's modulus, $S_{Ten}$ = tensile strength and r = density friction, because this leads to ultra-low friction forces at the sliding interface and therefore low wear rates. In the synovial joints of humans and animals, ultra-low friction is achieved through a very complex lubrication system called micro-elastohydrodynamic lubrication [32]. This special form of lubrication creates a thin-lubricant film between the sliding surfaces through an intricate combination of biomechanical and biomolecular factors acting at a variety of scales [33].

The coefficient of friction of synovial fluid has been measured to be as low as 0.002 [33] (this means that the friction force is 1/500$^{th}$ the normal force). Incredibly, this is 25 times better than engineers have achieved with artificial joint replacements, where the coefficient of friction is typically 0.05 [33].

## SPECIALISED FIBULA LINKAGE MECHANISM

The fibula is well known to provide stability to the ankle joint. One researcher states:

> The whole fibula including the head is essential for the stability of the ankle joint complex, and the distal fibula is responsible for stabilizing the ankle mortise during external rotation and inversion [10].

Another researcher states:

> In recent years, there has been an increasing recognition of the importance of the fibula and the tibiofibular ligaments to the biomechanics of the lower limb as a whole and to the ankle joint in particular [11].

The fibula stabilises the ankle through a type of linkage system with multiple bars [12], as shown in Figure 9. The long bars represent the tibia and fibula. The two long bars are connected by other bars via joints which can modelled by spherical joints and sliding joints [12]. One advantage of the fibula is that it increases the moment arm (mechanical advantage) of muscles acting on the ankle-foot complex. A second advantage is that the fibula increases the attachment area for muscles and therefore allows more muscle to act on the joint.

Linkage mechanisms in animal joints are well known to allow optimization of parameters like mechanical advantage, kinematic amplification and actuator location [34]. In engineering systems it is well known that linkage mechanisms (like four-bar linkages in car suspensions) are an important means for optimising a mechanical system.

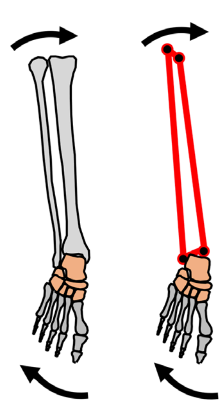


**Figure 9: Multi-bar linkage representation of the fibula bone.**
**doi:**10.5048/BIO-C.2022.3.f9

## ANSWERING THE "BAD DESIGN" ARGUMENTS OF NATHAN LENTS

### Answering the claim that bones are functionless

Lents believes that either most or all the bones of the ankle-foot complex have no purpose or function [13]. At the very least, he believes the five small bones of the midfoot are useless. However, this paper has shown that all the bones of the ankle-foot complex have very important roles in the specialised design features. In particular, the five bones of the midfoot have multiple functions (Section 5).

### Answering the claim that the fibula is not needed

Lents claims that the fibula bone (the small bone of the lower leg) is not required [13]. However, as shown in Section 7, the fibula provides essential stability to the ankle joint during pronation by forming a multi-bar linkage mechanism [12].

### Answering the claim that a fused ankle structure is best

If the ankle-foot complex were badly designed, it should not be difficult to define a better design. Lents has attempted to define a better design by claiming that a fused ankle joint would be better. Lents states:

Because many of the bones of the ankle do not move relative to one another, they would function better as a single, fused structure, their ligaments replaced with solid bone. Thus simplified, the ankle would be much stronger (see [13], p. 29).

It is wrong to say that many of the bones of the ankle do not move relative to each other because it is well known that the bones have significant relative movements [9]. It is also wrong to state that a fusion would be better and stronger. It is well known in the medical field that ankle fusions lead to a degradation of ankle performance. One hospital report states: "Walking on rough ground is difficult after [an ankle]… fusion. Most people cannot play vigorous sports such as squash … after a … fusion" [35]. Another medical report states: "Once [an ankle] joint has been fused, the joints … above and below the joint take on more strain" [36]. There are some pathological conditions such as tarsal coalitions that cause fusion of bones in the midfoot and, in such cases, the functionality of the foot is always significantly degraded [37].

In terms of engineering principles, it is also wrong to state that a fused structure would be stronger. A fused ankle would actually be significantly weaker for two main reasons. Firstly, the loads on the joint would be much higher when the shock-absorbing flexibility of individual joints was removed. Secondly, as shown in Section 6.2, a solid beam structure is much weaker than an elemental arch for a material like bone.

The fact that Lents cannot propose a superior design for the ankle confirms the weakness of his "bad design" arguments.

### Answering the claim that the ankle joint is always malfunctioning

To support his theory of bad design, Lents claims that the ankle joint is always malfunctioning. Lents claims:

> [The reason] sprain ankles are so common … [is that] the ankle is a hodgepodge of parts that can do nothing but malfunction (see [13], p. 29).

This statement makes the error of not differentiating between failure due to misuse and failure due to bad design. The importance of this differentiation can be illustrated by analogy with a modern car. Most modern cars are well designed and very reliable when in good condition and used properly. However, despite the high quality of design, a modern car will fail if overloaded or neglected, or if it is simply very old. Therefore, when considering malfunctions in joints it is important to check why there was a malfunction. If the ankle-foot complex malfunctions due to overload, neglect, or health issues, this does not mean the design can be judged as bad.

Not all types of failure are related to the quality of design. For example, when a Formula 1 car has tires that last just one hour, it is not because of bad design but because the car is deliberately meant to be operated at extreme levels of performance. In a similar way, when elite athletes train at extreme levels it is quite common that they experience occasional strains. They are willing to push their body to the limit of performance because of the large rewards that can be achieved.

Table 3 summarizes five types of failure that are not related to the quality of design.

Research shows that the ankle joint is remarkably robust when it is looked after. For example, one major research study showed that running is rarely associated with acute ankle sprain if runners take basic precautions [38]. Research into soccer has showed that ankle injuries are almost always associated with severe impact rather than running [39]. Other studies have shown that other common causes of ankle injuries are inappropriate types of studs and uneven or hard playing surfaces [40]. The performance of the human foot is very impressive from an engineering perspective. The American National Institute for Health recommends walking four miles per day [41]. That equates to 116,000 miles over an 80-year lifespan. Elite long-distance runners are well known to train more than 100 miles per week. In a 20-year running career, that equates to 100,000 miles of running. Such endurance is far beyond that of the best engineering prosthetic and robotic feet.

It is also important to recognise that a multifunctioning device like the ankle-foot complex involves a trade-off between individual performance factors. For example, it is impossible to maximise both compactness and strength. In multi-objective design, the aim must be to find the best compromise, and the ankle-foot complex achieves that compromise very effectively.

**Table 3: Types of failure not related to design**

| Type of failure | Engineering example | Human example | Consequence |
|---|---|---|---|
| Extreme use | Formula 1 | Elite sport | Risk of strains |
| Overload | Exceed weight limit | Obese | Structural failure |
| Neglect | No maintenance | Poor shoes | Breakdowns |
| Aging | Old rusting car | Old age | Weakness |
| Faulty production | Faulty component | Genetic fault | Breakdowns |

### Answering the claim that engineers would not design with so many parts

Lents makes two claims in support of his opinion that engineers would not copy the design of the ankle joint. First, he says that no engineer would design a joint with so many separate parts (see [13], p. 29). Second, he says that no modern mechanical engineer would design a joint with such an obvious liability as the Achilles tendon (see [13], p. 25). Lents provides no references or support for these claims. Moreover, both are clearly contradicted by the scientific recommendations that are coming from research on robotic feet, prosthetic feet, and ankle joint replacement surgery.

In the case of robotic feet and prosthetic feet, researchers are recommending that engineers copy the design of the foot to produce better functionality [42]. At present, the design of human feet is such that the human foot is far superior to the best prosthetic and robot feet [43–45]. In the case of ankle joint replacement (arthroplasty), researchers are also recommending that engineers copy the anatomy of the human ankle [46]. Indeed, researchers have reported that recent improvements in ankle arthroplasty have come about by copying aspects of human foot anatomy [46].

It is interesting to note that past ankle replacements have been found to be not much better than fused joints [46–47]. Whereas knee and hip replacements have been successful in terms of representing a significant improvement over damaged joints, ankle replacements have not had the same level of success. When you consider that replacement knee and hip joints are still inferior to the original natural joint, this illustrates that the ankle joint is an extremely difficult joint to create.

The author of this paper has nearly 40 years' experience of engineering practice, teaching and research, and has published over 200 technical articles relating to the science of design. From his experience, the multiple parts of the ankle joint are exactly what an engineer would specify for a high-performance multifunctioning joint.

## CONCLUSIONS

Modern discoveries in biomechanics have shown that Leonardo da Vinci was absolutely correct to conclude that the human foot is a masterpiece of engineering. There are four main conclusions from this study.

**Table 4: Specialised design features in the ankle-foot complex**

| | Specialised feature | Sub-functions | Role of hindfoot and midfoot bones |
|---|---|---|---|
| 1 | Triple-arched structure | • Stiff lever (medial arch)<br>• Flexible arch (lateral arch)<br>• Stiffening arch (transverse arch)<br>• Three-point contact | Four of the midfoot bones are essential for the transverse arch |
| 2 | Multi-functioning midfoot | • Shock absorber<br>• Load-bearing (pronation)<br>• Kinematic interface (pronation)<br>• Structural interface (axial loads)<br>• Stiffening arch (for medial arch) | All five bones of the midfoot needed for the functions |
| 3 | Elastic hinge joints | • Flexibility<br>• Load bearing<br>• Energy storage<br>• Fail-safe<br>• Ultra-low friction | Seven bones of midfoot and hindfoot create multiple joints to produce significant cumulative joint movement |
| 4 | Fibula linkage mechanism | • Fine tune mechanical advantage<br>• Maximise muscle volume | Fibula essential for ankle stability |

### 1. There are four highly specialised design features in the ankle-foot complex

This paper has described four highly specialised mechanical features of the ankle-foot complex that show a very high degree of complexity and fine-tuning. Table 4 summarises the four specialised features together with their sub-functions and the role of the bones in the ankle-foot complex. These four specialised features represent ingenious solutions for performing multiple kinematic and structural functions in a highly compact design.

### 2. The ankle-foot complex is superior to human-engineered joints

The relatively poor performance of prosthetic feet, robot feet, and replacement ankles (Section 8.4) confirms that bipedal movement involves extremely demanding requirements and that the human foot is an example of masterful engineering.

This paper has focused on the mechanical design of the joints of the ankle-foot complex. However, it should be noted that the actuation [48], sensing [49] and control of the foot involves additional very sophisticated engineering design.

### 3. Lents' bad design arguments are contrary to scientific evidence

The claims of bad design by Nathan Lents have been shown to be contrary to scientific evidence. All the bones of the ankle-foot complex have been shown to have important functions. When the ankle joint malfunctions or degrades, it is not because of design issues but because of misuse, aging, or health issues.

### 4. Engineering insight explains form and function

This paper has helped to explain form and function in the ankle-foot complex, such as the rationale for each of the seven bones and the layout of those bones. In particular, it has shown that each of the five midfoot bones are needed to form the optimal kinematic and structural interface between the forefoot and the hindfoot.

## ACKNOWLEDGEMENTS

This research was carried out at Cambridge University as part of a Visiting Research Fellowship in 2021. The support of the Discovery Institute to fund the fellowship is gratefully acknowledged.

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