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Research Article

Basic Principles of Morphometrics and Functional Foot Motion

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Abstract

Introduction: Significant obstacles remain before an understanding of normal functional foot and ankle motion is achieved. Although the remaining challenges are formidable, they are not insurmountable. A systematic approach to functional morphology research should help.

Background: Despite an arsenal of investigative tools that have been developed and implemented, much of it has not been organized so that it can be translated into favorable clinical outcomes which will continue to adversely impact reconstructive procedures. Understanding the more detailed abstruse motions of each bone and their articulating counterparts is a requirement.

Methods: A series of principles most likely to facilitate a basic understanding of morphometrics and functional motion was complied. The list was not comprehensive but focused solely on its applicability and advancement of ideas pertinent to the foot and ankle. It was not designed as original research or a review but as a guide for anyone interested in morphology and functional motion of the foot and ankle. Comparative anatomy, physical examination of in vitro skeletal specimens, photography, computed tomography, methods of morphometric selection, 3-axis coordinate systems and centers of rotation, the concept of polyaxial planes of motion, the benefits of initially developing prototype models to simplify kinematic and kinetic studies, and the importance of differentiating normal morphology from variables and those that cause deformities was examined.

Results: The basic concepts proposed support specific methods of examination and establishing 3-axis coordinates and center of rotation in every bone, accomplished with an emphasis on asymmetrical morphometric selection. Axes are always positioned distal, in the bone just proximal to the one under consideration. The effects of polyaxial motion on individual bones and joints is shown to be applicable to morphometrics. Select morphometrics are shown to be responsive to extrinsic and intrinsic forces, and it is demonstrated that prototype kinematic modeling can be reliable enough to be implemented in clinical settings.

Conclusion: Our proposed principles do not support an expansion of the currently available tools but rather encourages that we focus on traditional investigative methods, current technology, and collaboration when researching functional motion and morphometrics of the foot and ankle.

Keywords: *Morphometrics; Functional Foot Motion*

Introduction

Physical anthropologists, morphological anthropologists and anatomists infrequently interact with physicians and surgeons despite a shared goal of deciphering foot function. Despite decades of research and the most sophisticated imaging techniques and motion analysis tools, many mechanical properties of the foot and ankle remain a mystery. The expansion of technology to glean more detail has met with only minimal success. To be fair, the foot is incredibly complicated (requiring external forces to facilitate change). Every bone has its own unique complex morphology. A prerequisite for moving forward requires a paradigm shift in thinking and methodology. Establishing a set of fundamental principles (a set of fundamental laws or theorems with numerous applications across a wide range of disciplines) to examine the relationship of morphometrics and forces seems like an appropriate way forward.

Principles of function and morphology in the foot and ankle

1. **The etiology of structural deformities cannot be determined until normal function is established:** This principle is self-evident but important to acknowledge in functional morphometric studies. Accurately defining system or deformity without knowledge of its individual parts is futile**.** The functionality of the foot and ankle will only be understood when the more detailed abstruse motions of each bone and their articulating counterparts are delineated.

2. **Comparative anatomical studies are helpful when defining motion in humans:** The famous French comparative anatomist Cuvier famously developed the principle of correlation of corresponding parts, in which he demonstrated that with extensive empirical knowledge of an individual's isolated parts, it was possible to infer the function of an entire organism. This method has been utilized by functional morphologists and physical anthropologists ever since. Morton's [1] early research compared the skeletal morphology of other primates to human specimens and his contemporaries helped shape our fundamental understanding of foot motion. Studies of other terrestrial and arboreal primates with less complicated skeletal systems has provided more insight into foot function [2]. Trinkaus [3] found that diaphyseal torsion in human first metatarsals was less than Neanderthal. Conroy and Rose [4] noted the most significant functional change in the early evolution of the mammalian foot was the progressive development of the superposition of the talus over the calcareous, permitting the more complicated movements of pronation-supination at the subtalar joint. Steinler [5] described morphological changes that were required by the foot to transition from quadrupedal to bipedal gait; morphometric adaptation of specific articulating surfaces for static balance requiring minimal muscular activity was required, and active muscular activity for dynamic propulsion.

3. **Some skeletal morphometrics are best defined by visual examination, photography and sequential computed tomography; collectively they are capable of providing highly accurate detail. Cadaveric morphometric studies involving the skeleton also provide reliable kinematic results:** There is a myriad of benefits derived by visual examination and working with photography of *in vitro* skeletal models. Hick's seminal research established a first ray axis with 15 cadaveric specimens [6], and Ebisu [7] demonstrated that the first ray moved independent of the foot and was capable of precipitating hallux abductovalgus. Johnson., *et al*. [8] performed a series of *in vitro* studies in which they demonstrated conclusively that the action of the peroneus longus resulted in eversion of the first ray. Nozaki and colleagues [9] used 37 anatomical landmarks to detail the morphology of the calcaneus. They found the female calcanei to be longer in length and shorter in height than males, with the medial process of the calcaneal tuberosity more inferiorly projected and shifted more laterally in females. These findings have clinical applicability because the incidence of HAV is higher in females.

4. **There exist a series of unique functions in every bone that defines its morphometrics and more generally, its contribution to the whole foot:** This principle is consistent with the theorem first proposed by Russell [10] that concluded that form followed function. Weil, in the Harvard University Press advanced the theory of symmorphosis: the size of the parts in a system must match its overall functional demand. The complexity of the foot must provide man with a functional capacity capable of coping with its highest functional demand, including a safety margin to prevent failure. One might add that the number of bones is as critical as their size.

Thomason [11], in his Functional Morphology in Vertebrate Paleontology, credits Lauder for establishing several areas of analysis in complex morphological systems, including skeletal anatomy, which encompasses bone shape, articular geometry (and borders), and quantitative and quantitative descriptors. More specifically in the foot, this list includes torsion in long bones and their medial and lateral lengths, the size, depth, and geometry of the plantar condyles, and the size, shape, and spatial relationships of the sesamoids.

5. **It is possible to establish a 3-axis coordinate system** in **every bone in the foot and ankle:** Thordarson [12] credited Lundberg for first establishing a 3-axis coordinate system in the foot. To standardize quantitative motion studies prior to kinematic research there must be, at a minimum, a reference point that is capable of describing a bone around the 3 cardinal axes. Traditionally, translation has been described as motion in a straight line, when the line of force passes through its center [13], and rotation is described as motion around a fixed axis which occurs when the line of force does not pass through its center. By definition, its motion is always perpendicular to the axis of rotation and the greater the distance between the line of force and the center of the object or center of mass the greater its rate of rotation [13]. Sagittal plane motion occurs around the x-axis, frontal plane motion occurs around the z-axis, and transverse plane motion takes place around the y-axis. Steiner reached a conclusion that all motion in the foot is rotational seems accurate [14]. The major obstacle is its placement, but there are a few methods to simplify its position. If a bone is examined with an understanding that the placement of a 3-axis coordinate system determines the center of rotation in the bone directly distal to it, then it becomes slightly less complicated. It cannot be place too proximal, otherwise motion cannot occur in the distal bone. Axes placement also requires morphometric markers such as condyles, or asymmetry between opposing sides that is likely to promote motion around 3 planes of motion.

6. **Motion cannot occur around a fixed axis or plane of motion in the foot because skeletal symmetry does not exist in any bone:** The closest the skeletal foot comes to exhibiting symmetry is the distal metatarsal border. Although the distal metatarsal surface may appear to be spherical, there may be a slight difference in radius of curvature around its y and z-axes. However, since the proximal phalanx and two sesamoids form an instantaneous center of rotation in the metatarsal head, the morphometrics of the metatarsal grooves and sesamoids negate any symmetry that might exist [15].

7. **All 3-axis coordinate systems must be positioned in the bone immediately proximal to it (with the possible exception of the calcaneus):** As an example, the first metatarsal 3-axis and center of rotation is positioned in the medial cuneiform; the medial cuneiform axes is located in the navicular, the cuboid axes is located in the calcaneus, and the talus center of rotation is located in the lower leg. Every bone in the foot (excluding perhaps the spherical distal metatarsal surface) is asymmetrical, so no stationary axis exists. Ultimately, an instantaneous center of rotation will describe all motion. The major obstacle is its placement, but there are a few methods to simplify its position. If a bone is examined with an understanding that its center of rotation defines motion in the bone directly distal to it, then it becomes slightly less complicated. It cannot be place too proximal, otherwise motion cannot occur in the distal bone. Axes placement also requires morphometric markers such as condyles, or asymmetry between opposing sides that is likely to promote motion around 3 planes of motion.

8. **Depending on the morphometrics and intersecting joint morphometrics, forces and motion in one joint will invariably increase or decrease motion in adjacent bones and joints:** Benink [16] and Van Langelaan [17] were early investigators to examine motion in the tarsal bones of the foot, doing so by stereo photogrammetric roentgen analysis. They concluded that integrated structures (bone) separated by joints are polyaxial and as such, independent motion is not possible. This principle extends beyond adjacent bones. Blackwood., *et al*. [18] found increased sagittal plane motion in the first, second and fifth metatarsal with calcaneal eversion as opposed to when it was maximally inverted, confirming the inter-relationship between the hindfoot and forefoot. Although the 3-axis coordinates of the proximal phalanx and two sesamoids have an instantaneous center of rotation located in the metatarsal head, the morphometrics of the metatarso-phalangeal-sesamoid joint complex directly influences distal metatarsal motion, which is different than the motion at its proximal end [15].

9. **Functional motion studies involving morphometrics are meaningless unless they account for at least one motion around a single axis of a 3-axis coordinate system:** At a minimum, this is a basic requirement. Developing simplified prototypes and may be an ideal approach to begin with.

10. **A complete understanding of foot mechanics will not occur until a comprehensive understanding of the morphometrics, and function of every bone is known:** Homberger [19] established specific investigative requirements that need to be followed when attempting to decipher motion in complex structural systems (foot). Ascertaining which specific morphometrics were relevant for any intended study is fundamental, although other disciplines, such as biomechanical principles, imaging, and kinematic observations will need to be integrated for any functional model to be complete.

    There is no shortage of notable morphological studies. Mason and Tanaka [20], in a *in vitro* study involving 42 cadaveric feet from 23 individuals, found three distinct medial cuneiform articular subtypes, ranging from a single facet, to three. All feet with a single articular surface exhibited hallux valgus deformities and in feet with trifacet articular surfaces, all feet were deemed normal. They also found a gender difference. Dykyj., *et al*. [21] analyzed the articular geometry of the first tarsometatarsal joint in metatarsus primus adductus and metatarsus primus rectus feet. Using a Coordinate Measuring Machine to define the three-dimensional (3D) facet ordinates of the metatarsal and cuneiform in 29 cadaver feet, they found statistical significance between subsets of primus adductus and rectus feet, gender, and both metatarsals and cuneiforms.

    There are plenty of morphological studies to begin assimilating them into prototype models.

11. **A complete understanding of functional motion of the foot will require the integration of morphometrics and kinematic studies:** Kinematics studies motion of joints without reference to the forces causing them. Examples include linear and angular displacement, velocities, center of rotation and acceleration. Kinetics is the study of forces causing movement [22]. In some cases, evaluating foot response to extrinsic forces it is exposed to is better understood from a GRF perspective. Although gravitation forces originate from proximal, it is the morphometrics of any part that is in contact with the horizontal surface that will dictate its motion. This concept is found frequently in the literature, but excluding gait plates, its applicability to functional foot models is almost non-existent. A simplified practical application of the mechanics of this is a foot that is exposed to uneven terrain, such as only partially stepping off a step. Because the GRF's are unevenly applied to the foot, the side which encounters the least amount of force will respond by moving around an axis somewhere in the foot. A quantity called the joint reaction force is defined which does not represent the bone on bone force, but is simply the sum of the forces due to gravity and the acceleration of segments, regardless of muscle forces crossing the joint [23]. Due to the asymmetry of the sesamoids and their respective groves and other plantar condyles and torsion in every structure that makes contact with the ground, in many cases it is easier to decipher skeletal motion from the perspective of GRF's.

12. **With a large enough data base, it will be possible to differentiate between normal skeletal variability and abnormal morphometrics:** Homberger [19] noted the importance of verifying the descriptive accuracy of morphological characteristics and account for any variations prior to attempting to defining if it exposes the system to failure. Nilsonne (1930) [24] and more recently Mancuso [25] both noted that most patients with hallux limitus had elongated first metatarsals in addition to a loss of arch height. Mayo in 1918 [26] noted the higher incidence of elongated metatarsals in HAV. Metatarsal length also varies by gender but precisely what constitutes skeletal variability, or an elongated metatarsal has yet to be precisely defined. A flattened distal articular surface of the metatarsal has been implicated in hallux limitus deformities [27], but radius of curvatures have yet to be established in large enough cohorts to actually define the deformity. And due to smaller metatarsals, this curvature will be less in females.

13. **The foot has and will continue to evolve in response to external stresses:** The surfaces that modern man walk on are distinctly different than in earlier times, the prevalence of obesity is now endemic in many societies, feet are now shod, and climate change is accelerating, which could have unanticipated effects on foot morphology and function. Evolutionary changes will occur in response to the environment, it is just a matter of time.

14. **Progress will always advance quicker when disparate disciplines routinely make collaboration a focus of their research:** If functional morphologists, anatomists, surgeons, and biomechanical experts make it a precedence to routinely share research that encompasses morphology and function, everyone will benefit.

Methods

A series of principles most likely to facilitate a basic understanding of morphometrics and functional motion was complied. The list was not comprehensive but focused solely on its applicability and advancement of ideas pertinent to the foot and ankle. It was not designed as original research or a review but as a guide for anyone interested in morphology and functional motion of the foot and ankle. Comparative anatomy, physical examination of *in vitro* skeletal specimens, photography, computed tomography, methods of morphometric selection, 3-axis coordinate systems and centers of rotation, the concept of polyaxial planes of motion, the benefits of initially developing prototype models to simplify kinematic and kinetic studies, and the importance of differentiating normal morphology from variables and those that cause deformities was examined.

Results and Discussion

The basic concepts proposed support specific methods of examination and establishing 3-axis coordinates and center of rotation in every bone, accomplished with an emphasis on asymmetrical morphometric selection. Axes are always positioned distal, in the bone just proximal to the one under consideration. The effects of polyaxial motion on individual bones and joints is shown to be applicable to morphometrics. Select morphometrics are shown to be responsive to extrinsic and intrinsic forces, and it is demonstrated that prototype kinematic modeling can be reliable enough to be implemented in clinical settings.

Conclusion

This list of principles pertaining to morphometrics and functional motion of the foot and ankle are not all inclusive; undoubtedly there are more. Some will withstand the test of time, and perhaps others may not. Hopefully, these principles will provide some guidance and help investigators refine their research objectives.

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