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Special Article

Current trends in the biokinetic analysis of the foot and ankle

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Abstract

Although the importance of studying the anatomy of structures of the ankle and foot joints is fundamental, evidence points to a low correlation between static and dynamic measurements; this could represent a problem in the study of the functioning of the ankle and foot during daily activities. The aim of the present study is to review the classic knowledge on ankle and foot biomechanics and present new concepts of functional biomechanics (3-dimensional biokinetic analysis) in order to clarify their clinical applications in assisting diagnostic and/or treatment decisions. For this, we performed a literature review and divided the article into 6 sections: (1) functional biomechanics of the ankle and foot; (2) dynamic joint stability; (3) functional stability mechanisms of the foot; (4) functional stability mechanisms of the ankle; (5) gait and running biokinetics; (6) the role of proximal joints in ankle and foot movement. At the end of this article, the reader should be able to understand how the 3-dimensional biokinetic analysis of the ankle and foot can contribute along with imaging examinations to the clinical setting, thus allowing the construction of a more complete profile of the patient. Such information could enable the identification of weaknesses and the implementation of objective interventions for each patient.

Level of Evidence V; Prognostic Studies; Expert Opinion.

Keywords: Activities of daily living; Ankle injury/pathophysiology; Joint instability/pathophysiology; Biomechanical phenomena.

Introduction

The foot supports all the weight exerted by the human body, which can eventually reach 4 to 6 times a person's normal weight[1]. It is the first body segment to absorb the reaction forces caused the contact against the ground in daily activities and sports movements, and it performs the transfer of forces through the proximal joints for power generation[2]. The foot is an anatomically complex structure, consisting of various bones and joints, as well as intrinsic and extrinsic muscles. These aspects provide the necessary mobility to absorb forces, along with a high capacity to change rigidity and be a robust lever arm for transferring forces to the ground[3].

In spite of the importance of studying the anatomy of the ankle and foot joints, evidence indicates a low correlation between static and dynamic foot measurements[4,5]. Böhm et al.[5] (2019) demonstrated that static measurements of foot deformities (performed using radiographs) explained only a small variation in foot movements during gait, especially in children with flexible flat feet. This was possibly related to an overload of the ankle and foot both statically and during different dynamic activities. These findings suggest that the function of the foot cannot be precisely assessed exclusively from manual clinical examinations, provocative tests, and static radiographic observations, although this is commonly performed in clinical practice.

Moreover, individuals with similar anatomopathological diagnoses have been reported to present different biokinetic findings, demonstrating that the functional assessment of specific movements should be seen as a complementary examination that is essential to the conventional practice of ankle and foot specialists[6]. The purpose of this article is to review the biomechanics of the foot and ankle combining

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classic knowledge with new concepts of functional biomechanics in order to lay the foundation for the clinical application of 3-dimensional (3D) biokinetic analysis in diagnostic and/or treatment decisions.

Functional biomechanics of the foot and ankle

Conventionally, the movements of the ankle and its muscular actions are studied either with the tibia as a fixed point for the free movement of the ankle and foot (usually named an open kinetic chain [OKC] movement) or with a fixed foot, for instance against the ground, where the movement would happen in the proximal segments and be named a closed kinetic chain (CKC) movement[7]. However, these approaches do not fully represent what happens during daily activities. The concept of functional biomechanics advocates that although one segment will always be the base for the other to move, both segments can be simultaneously mobile in any trivial activity. The main difference between conventional and functional biomechanics is that the latter considers that the function of joints and segments cannot be separately observed. The central nervous system (CNS) works as the generator of complex movement patterns based on muscular synergisms, aiming to accomplish a motor task instead of accounting for individual muscular actions[8]. Following this line of reasoning, 3D biokinetic analyses are meant to identify the role of each anatomical, joint, and muscular structure in the functional capacity of an individual throughout his or her daily activities. To facilitate the understanding of this relatively new area of study, it is necessary to establish how the main pillars of functional biomechanics are applied to the study of foot and ankle function.

Dynamic joint stability

Rienmann and Lephart[9] (2002) define dynamic joint stability as the ability of a joint to remain or readily resume to its proper alignment through an equalization of forces. Evidence suggests that the control of active joint stability is orchestrated by the neuromuscular system and not by isolated muscle strength or range of motion[10], highlighting the importance of the CNS as a functional maestro.

The ability to generate safe movement and to improve performance depends on the movement of joints in segments with stable bases. Literature on the importance of functional ankle stability for injury prevention and rehabilitation[2,6,11] is extensive and relates chronic ankle instability to a lower capacity of generating functional strength by the triceps surae muscle[11], lower power production during jump propulsion[12], and a higher risk of ligament and cartilage injuries[13]. Therefore, reducing this instability through specific training or surgery is crucial and should be done before the adoption of an overloading activity such as an increase in sports performance. In order to understand some of the strategies for reversing non-surgical instabilities, it is necessary to address the structures that participate in the joint stability of the foot and ankle.

Functional stability mechanisms of the foot

The main structure that generates stability in the human gait is the foot. Functionally, the foot has 3 main roles:

1) To be a stable base of support for movements of the proximal segments;
2) To assist in the absorption of ground reaction forces;
3) To be a powerful lever arm for the ankle muscles during the propulsion of gait and sport movements.

The intrinsic and complex role of the plantar arch of the foot in maintaining stability and mobility has been the subject of studies in several areas from the Renaissance era, with Leonardo Da Vinci[14], to anatomists of the last century[15] and present day[4]. The medial longitudinal arch (MLA) has been the most studied structure because its load sharing system (arch load-sharing system) is believed to be essential for the proper functioning of the foot[16]. It works as a spring system, changing foot stiffness and allowing deformation for absorbing loads while creating a robust segment for transferring forces to the ground. For a more detailed understanding of the role of the medial longitudinal arch, please refer to Kirby[16] (2017).

Despite widespread research on this reductionist 2-dimensional (2D) view of the MLA, some of the evidence indicates that it functions as a 3D structure. Some authors suggest that the plantar arch should be named “plantar dome,” due to the importance of other passive, active, and neuromuscular structures in maintaining the plantar arch[2]. This theory has been confirmed by cadaveric experiments showing that the resection of the plantar fascia reduced foot stiffness by less than 25%[17]. On the other hand, engineering principles demonstrate that even thin structures, when folded in the transverse direction, increase their longitudinal stiffness; this concept that can be easily demonstrated by a slice of pizza curved across in our hands. Recently, Venkadesan et al.[18] (2020) applied these concepts of transverse arch stiffness and observed that the resection of the transverse arch reduced foot stiffness by more than 50%, highlighting its important role in the maintenance of the plantar dome. For an illustration of the effect of transverse stiffness on longitudinal stiffness, the authors suggest the following video: https://youtu.be/adt3sH9O_vE.

Another aspect associated with the functioning of the plantar arch is the windlass mechanism, which is widely observed in orthopedic clinical practice through the Jack’s Test[19]. During this test, the hallux extension produces a tension in the plantar aponeurosis, which brings the calcaneus closer to the metatarsophalangeal joints[20] (Figure 1). In association with passive structures, the posterior tibial muscle begins to act concentrically and blocks the midtarsal joints to increase foot stiffness[20]. Functionally, the windlass mechanism occurs with the hallux as a fixed point and with the movement of the metatarsophalangeal joint (Figure 2). This mechanism is initiated by tibiotalar dorsiflexion as the tibia advances over the talus in the midstance (MS) phase of the gait[20]. In the terminal stance (TS) phase, load on the forefoot region increases, activating the fibularis longus muscle and inducing the windlass mechanism and the elevation

Figure 1. The windlass mechanism demonstrated passively: A hallux extension produces a tension in the plantar aponeurosis, which brings the calcaneus closer to the metatarsophalangeal joints.

Figure 2. The windlass mechanism actively provoked on terminal support phase: The activation of fibularis longus and tibialis posterior muscles collaborates in maintaining the plantar arch for adequate triceps surae function and ankle stabilization.

of the calcaneus on a rigid forefoot base, thus creating an effective lever arm to generate propulsion for the second half of the support phase[20].

Increased mobility of the midfoot and reduced mobility of tibiotalar dorsiflexion and hallux may impair the windlass mechanism and contribute to increased foot stiffness in this phase[21]; individuals with flexible flatfeet may not be able to create a rigid base, causing the axis of movement to move towards the midtarsal joints so the lever arm is reduced[21]. As a form of compensation, the triceps surae is more intensely activated and produces more strength; this overload may lead to painful conditions such as Achilles tendinopathies or muscle injuries. Moreover, inadequate triceps activation and/or strength also increases ankle instability[21].

Functional stability mechanisms of the ankle

Several studies have demonstrated changes in the movement patterns of hips, knees, and ankles in individuals with chronic ankle instability[2,6,22], demonstrating that the same condition can lead to different motor adaptations and each case requires individual evaluation. The motor variability among these individuals may reflect either an attempt to explore alternative stabilizing strategies or an inadequate sensory-motor control[23]. In addition, the arthrogenic inhibition of the fibularis longus has been related to continued instability even after the restoration of triceps surae muscle strength[24].

According to Hertel et al.[25] (2002), individuals with ankle instability can be classified into 2 major groups: those with mechanical ankle instability (MAI) and those with functional ankle instability (FAI). MAI is defined as a pathological laxity after ligament injury, while FAI is a subjective symptom or sensation of instability due to proprioceptive deficits and changes in neuromuscular functions.

Several clinical tests are commonly used to measure ankle stability, and subjective measurements of the eversion/inversion of the heel can be performed with activities such as unipodal support and walking on a treadmill. However, in addition to the measurement errors intrinsic to subjective tests, clinically assessing dynamic joint stability does not guarantee the functional competence of the ankle and foot in daily tasks and sports. Despite being more affordable and easier to perform, 2D assessments can present important measurement errors even in individuals with small rotational changes in the ankle and foot[26]. It should also be taken into account that ankle stability is direction- and task-dependent[24], and the ability of an individual to maintain joint stability in one direction does not mean he or she will be able to do so in other directions. It is necessary to evaluate all 3D components of foot and ankle stability to ensure a safe return to daily activities and sports. Therefore, the functioning of the foot and ankle should be tested and analyzed in different activities. In this review, we will summarize relevant information currently published on gait and running.

Gait and running biokinetics

Human gait and running can be divided into stance and balance phases. In gait, the support phase is subdivided into 4 phases: load response (LR), MS, TS, and pre-swing (PS)[1] (Figure 3). In running, the support phase is subdivided into 2 phases: LR and propulsion response (Figure 4). During LR in a non-pathological gait, in the sagittal plane, the foot drops (heel rocker) with a plantar flexion movement eccentrically controlled by the tibialis anterior muscle. In the coronal plane, there is an eversion movement of the ankle, eccentrically controlled by the tibialis posterior muscle. At this moment, motion control is achieved by reducing the stiffness of the foot and turning it into a structure that is able to absorb mechanical loads[1]. In running, the role of eccentric eversion control increases due to increased ground reaction forces. In runners whose initial contact happens with the heel (rearfoot strikers), the sural triceps has a secondary effect in load absorption by preventing excessive advancement of the tibia[1]. On the other hand, in runners whose initial contact occurs with the midfoot or forefoot (midfoot/forefoot strikers), the sural triceps assumes a primary eccentric role, which may increase the risk of Achilles tendinopathies and injuries in the tibialis posterior[27] when no proper training is employed.

The ankle rocker phase during MS is characterized by a rotation of the tibia over the foot, which is fixed on the ground on unipodal support, while the plantar arch is maintained by activating the posterior tibialis and intrinsic muscles of the foot. During TL and PS, the forefoot rocker phase happens when the heel rises from the ground and begins the propulsion phase. At this moment, the sural triceps activation, mostly through the soleus muscle, has the important role of limiting the anteriorization of the tibia and inducing knee extension. The fibularis longus depresses the first metatarsal head and contributes to the formation of the plantar arch and stabilization of the ankle joint. In running, the soleus has an additional propulsion role since it is responsible for more than 50% of the horizontal acceleration of the runner's center of mass[1].

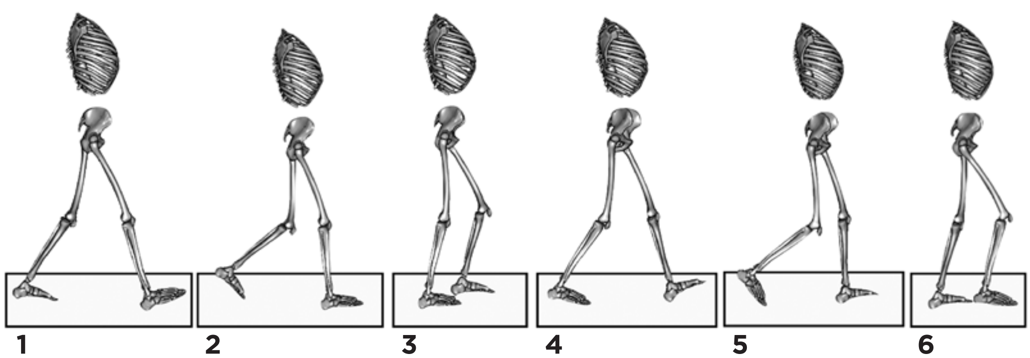

Figure 3. The gait cycle. Using the light limb as reference: (1) initial contact; (2) load response (LR); (3) midstance (MS); (4) terminal stance (TS); (5) pre-swing (PS); (6) swing (Image by Biocinetica Laboratório do Movimento Ltda, Rio de Janeiro, Brazil).

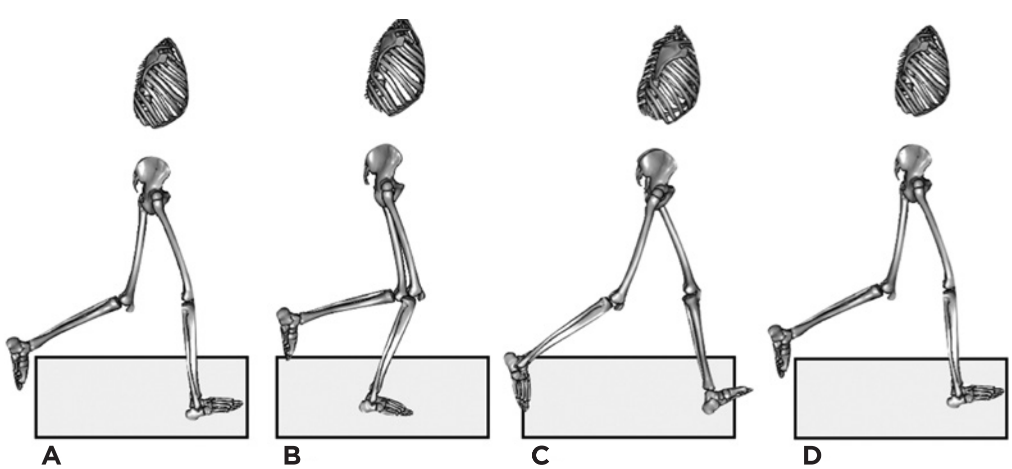

Figure 4. The running cycle. Using the right limb as reference: (A) initial contact; (B) LR; (C) propulsion; (D) swing (Image by Biocinetica Laboratório do Movimento Ltda).

The role of proximal joints in ankle and foot movement

Although it is easy to suppose the influence of neighbor and distant joints in the control of the foot and ankle, the identification and measurement of such influences only recently has been deeply studied. Cavalin et al. [28] (2018) found a strong association between hip adduction and ankle eversion in healthy runners, where 50% showed a descending relationship (hip influencing the ankle), 25% showed an ascending relationship (ankle influencing the hip), and 25% presented a synchronic relationship over time (Figure 5). Other authors have also demonstrated the influence of the ankle dorsiflexion range of motion in femoral medialization, a movement dysfunction often referred as "dynamic valgus". The proximal chain can influence and be influenced by distal changes and interfere on the loading of joints and segments as a whole[29] (Figure 6).

Conclusion

Human motion happens as a system where many variables may individually or collectively influence the loading, mobility, and stability of any one joint or segment. Similar to an

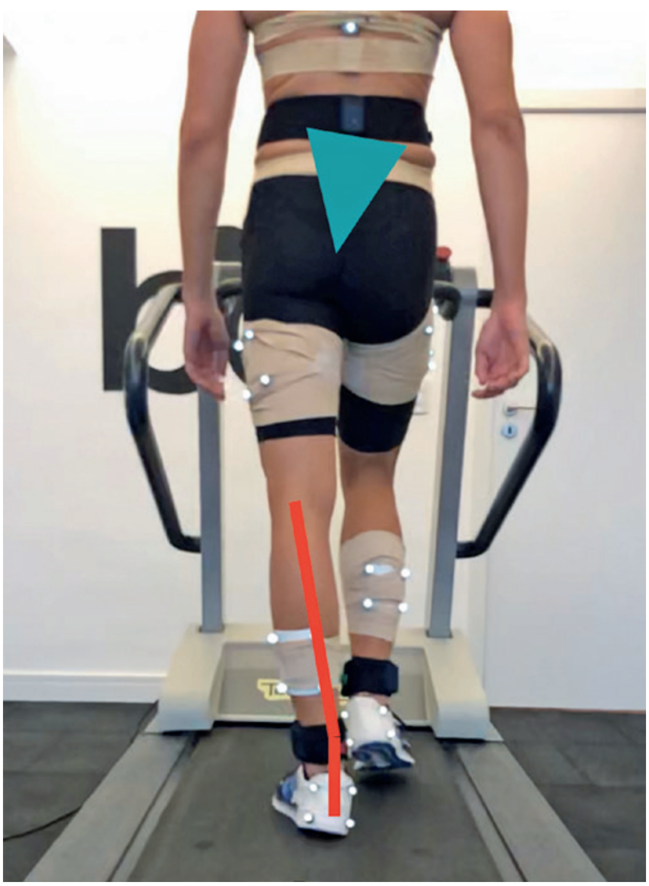

Figure 5. Individual walking on a treadmill at 4.3km/h showing, in the coronal plane, the influence of a pelvic contralateral drop on ankle eversion.

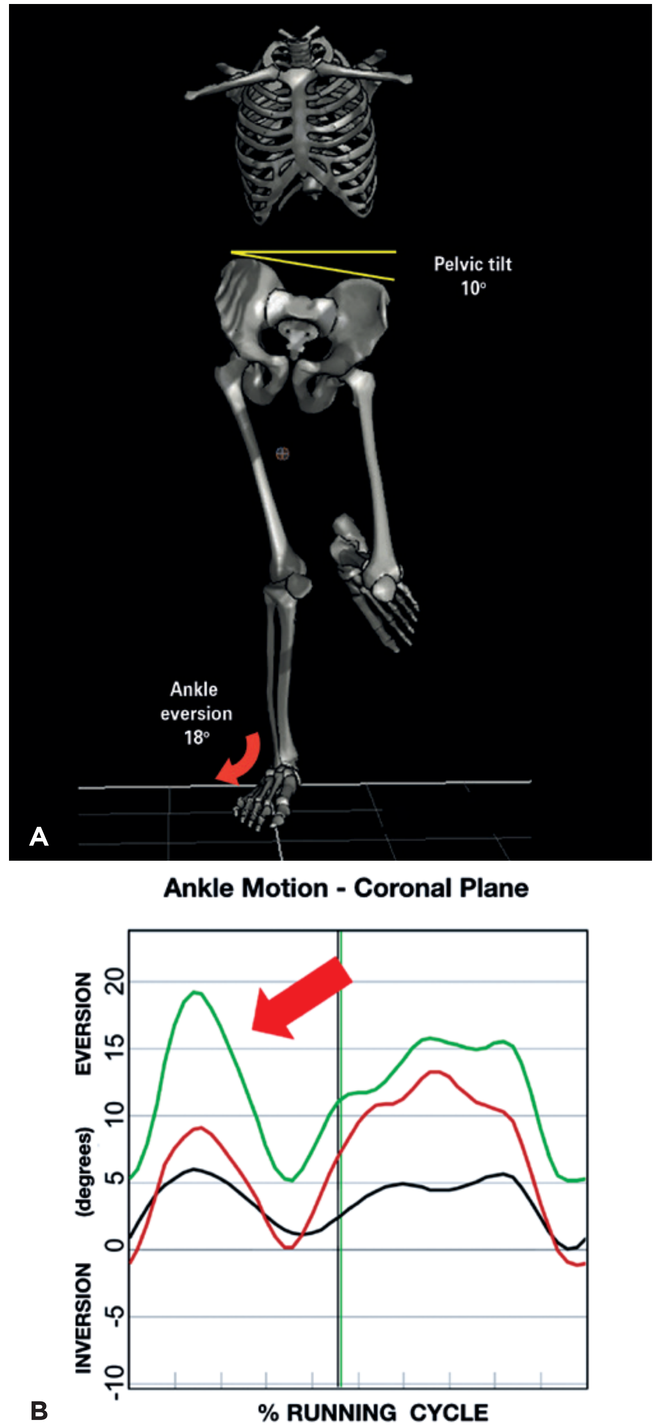

Figure 6. Three-dimensional biokinetic analysis image (A) and graph in degrees (B), in the coronal plane, of a 35-year-old male recreational long-distance runner diagnosed with plantar fasciitis. Peak right ankle eversion (18°) influenced by a peak contralateral pelvic drop (10°) in the stance phase of running. Red arrows: excessive ankle eversion; yellow lines: excessive contralateral pelvic drop; green line: right ankle motion; red line: left ankle motion; black line: expected ankle motion (Image by Biocinetica Laboratório do Movimento Ltda).

airport network, when one terminal is out of order, the others are overloaded, but eventually all planes must get to the ground safely.

The adequate functioning of the foot and ankle depends on the activities of passive tissues and muscles and the neuromuscular control of local and distant joints. Any changes to this system may lead to functional incapacity and subsequent lesions and/or pain. The study of the functional biomechanics of the ankle and foot, in addition to a clinical investigation and imaging exams, contributes to a more complete understanding of the problems of each patient. For these reasons three-dimensional biokinetic assessments have become valuable tools for identifying the weakest links in the movement chain in an objective, measurable, and reproducible manner.

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