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Review

Hallux valgus in children. Biomechanical aspect: A literature review

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ABSTRACT

BACKGROUND: The study comprehensively describes the issues of the normal biomechanics of the first toe, first metatarsophalangeal joint, and first ray when walking. Understanding the fundamental processes of the functioning of these structures is a leading aspect in the study of the etiopathogenesis of hallux valgus and is important in treatment planning.

AIM: To analyze the literature concerning the kinematic and kinetic indicators of the first toe, first metatarsophalangeal joint, and first ray of the foot when walking in the final support phase.

MATERIALS AND METHODS: The characteristics of periods, gait phases, kinetic and kinematic movements were analyzed.

RESULTS: To perform a "push-off" when walking, sufficient extension of the first toe in the first metatarsophalangeal joint is necessary, which is fully accomplished only in combination with flexion and eversion of the first ray of the foot. Muscular control of the position of the first toe in the first metatarsophalangeal joint is carried out by the short and long flexors of the first toe with the sesamoid apparatus of the first metatarsal bone, whereas functions of the first ray and midfoot joints are stabilized by the peroneus longus muscle.

CONCLUSIONS: The influence of kinematic and kinetic indicators of movements in the lower-limb joints in the horizontal plane on the flexion of the first ray and extension of the first toe in the metatarsophalangeal joint and the determination of the nature and volume of movements in midfoot joints in various phases of the gait cycle remains a pressing issue.

Keywords: *hallux valgus*; equinoplanovalgus foot deformity; first ray of the foot; first metatarsophalangeal joint; gait analysis.

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Научный обзор

Вальгусная деформация I пальца стопы у детей. Биомеханический аспект. Обзор литературы

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АННОТАЦИЯ

Обоснование. В работе подробно освещены вопросы нормальной биомеханики I пальца, первого плюснефалангового сустава, первого луча при ходьбе. Понимание фундаментальных процессов функционирования данных структур — ведущий аспект в изучении этиопатогенеза вальгусной деформации I пальца стопы, а также имеет первостепенное значение при планировании лечения.

Цель — проанализировать мировую литературу, посвященную кинематическим, кинетическим показателям I пальца, первого плюснефалангового сустава, первого луча стопы при ходьбе в конечные фазы периода опоры.

Материалы и методы. В работе проанализирована литература, в которой рассмотрены характеристики периодов, фаз походки, кинетических и кинематических характеристик движений.

Результаты. Один из важнейших элементов биомеханически правильной походки — создание толчка в конечной фазе опоры. Для его совершения необходимо достаточное разгибание I пальца в первом плюснефаланговом суставе в сочетании со сгибанием и эверзией первого луча стопы. Мышечный контроль положения I пальца в первом плюснефаланговом суставе осуществляют короткий и длинный сгибатели I пальца стопы с сесамовидным аппаратом I плюсневой кости. Функцию стабилизатора первого луча и суставов среднего отдела стопы выполняет длинная малоберцовая мышца с помощью активации механизма блокировки переднего отдела стопы.

Заключение. Актуальным вопросом остается исследование влияния кинематических и кинетических показателей движений в суставах нижних конечностей в горизонтальной плоскости на сгибание первого луча и разгибание I пальца в плюснефаланговом суставе, а также определение характера и объема движений в суставах среднего отдела стопы в различные фазы цикла походки.

Ключевые слова: *Hallux valgus*; эквино-плано-вальгусная деформация стоп; детский церебральный паралич; первый луч стопы; первый плюснефаланговый сустав; анализ походки.

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BACKGROUND

Currently, *hallux valgus* deformity of the first toe (hereinafter *hallux valgus*) is one of the most common orthopedic diseases. Among the adult population, the incidence ranges from 25% to 35%, reaching 44% in women and up to 22% in men [1–3]. According to T.E. Kilmartin et al., juvenile *hallux valgus* among children aged 9–10 years is registered in 2.5% [4]. As reported by S. Nix et al. [5], the incidence of juvenile *hallux valgus* averages 7.8%; with age, this figure increases, and it is 23% in people aged 18–65 years, whereas it is 35.7% in people aged >65 years. The authors note the prevalence of the disease among women by 2–3 times in all age groups and the deformity progressing with increasing age.

Valgus deformity of the first toe is a polyetiological multifactorial disease. Depending on the etiological factor, it can occur as idiopathic *hallux valgus* in adults, juvenile idiopathic *hallux valgus* [4, 6–8], *hallux valgus* in patients with rheumatoid arthritis [7, 9, 10], posttraumatic *hallux valgus* [11–13], and *hallux valgus* in patients with neurological pathology [7]. For each disease group, the mechanism of the deformity development has been established [14, 15]. However, the described etiopathogenetic factors in various disease forms are not significant and are widely discussed in the literature.

In our opinion, to study the deformity pathogenesis and when planning the prevention and treatment of children with this disease with such a wide range of etiological factors, the fundamental aspects of the biomechanics of the foot and the entire lower limb must be understood.

The modern anatomical and functional concept of *hallux valgus* considers the deformity of the first toe, components of the first metatarsophalangeal joint, and first ray of the foot in static conditions, i.e., in a standing position, which corresponds to the midstance phase of the gait cycle. However, this phase does not fully reflect the functional role of the aforementioned forefoot components.

The main functions of the first toe, first metatarsophalangeal joint, and first ray of the foot are implemented in the final phases of the stance phase, i.e., the terminal support and preswing. During these phases, a pushoff is formed, ensuring the movement of the body's center of gravity forward. Impaired pushoff will lead to the activation of compensatory mechanisms for propulsion [16–19].

In the Russian literature, no studies have examined kinetic and kinematic parameters and muscle control of the components of the first metatarsophalangeal joint during walking.

The study aimed to analyze the world literature on the kinematic and kinetic indicators of the first toe, first metatarsophalangeal joint, and first ray of the foot when walking in the final phases of the stance phase.

MATERIALS AND METHODS

The search for scientific publications was performed in PubMed, eLibrary, Cochrane Library, Elsevier, and Wiley Publishing Library without limiting the search period for the following query: *hallux valgus*, first ray of the foot, gait analysis, equino-plano-valgus foot deformity, and first metatarsophalangeal joint. The work included data from 67 scientific articles and publications. The presented descriptive characteristics of periods, gait phases, and terminology of kinetic and kinematic data of locomotion are used in Russian and international literature [16, 18].

RESULTS

Characteristics of the final phases of the stance phase

The primary source of energy during walking, providing pushoff and propulsion, i.e., forward movement, in the terminal stance and preswing phases of the stance phase, is the ankle joint, stabilized by the triceps surae muscle on one side and the forefoot, performing a third rocker on the surface, on the other. The third rocker is characterized by the forward movement of the body caused by the extension of the toes in the metatarsophalangeal joints, due to the projection of the body's center of gravity in the toe area. Normal functioning of the forefoot elements during walking is necessary to ensure biomechanical stability of the entire lower limb in the final phases of the stance phase [16–19].

The terminal stance phase requires a single support. It begins with lifting the heel of the supporting foot and continues until the contralateral limb makes contact with the surface. In the terminal stance phase, the projection of the ground reaction force vector is in the forefoot area, which creates a significant flexion torque in the ankle joint. However, eccentric contraction of all the foot flexor muscles, namely, gastrocnemius, soleus, flexor digitorum longus of the first toe, flexor digitorum longus, tibialis posterior, peroneus longus, and peroneus brevis, has a blocking effect on ankle joint dorsoflexion within 10° to facilitate heel lift along with forward movement of the shin. In this case, the heads of the metatarsal bones and toes become a support for the entire body, and extension in the metatarsophalangeal joints creates the condition for moving the projection of the body vector forward. This process is also called rolloff. Further displacement of the projection of the center of gravity of the body beyond the area of support represented by the toes leads to a free fall of 60% of the body mass forward from a height of approximately 1 cm in 0.02 s (Fig. 1*a*) [4]. However, contact with the surface of the contralateral limb, which ends

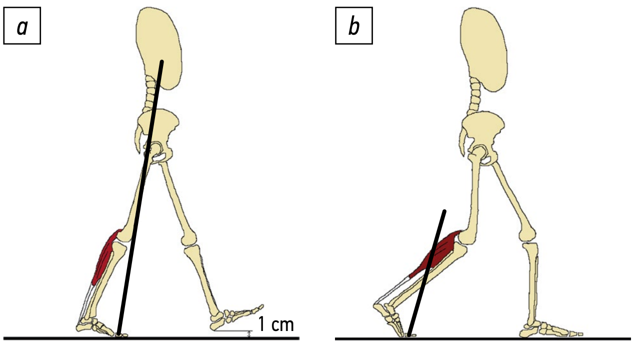

Fig. 1. Phases of terminal support (*a*) and preswing (*b*). The black line indicates the vector of the support reaction forces, or the vector of the body

the swing period, prevents the body from falling and ensures the stabilization of the position of the center of gravity above the newly formed support area [16–19].

The kinematics of the lower limb of this phase is as follows: inversion in the subtalar joint reaches a neutral position; by the end of the phase, the tibia rotates medially relative to the thigh, whereas the knee joint is unlocked, and the possibility of flexion in it by 10° is created. The femur rotates outward relative to the pelvis, the hip joint extends up to 20°, and the pelvis is tilted forward up to 10°, externally rotated by 5° with its neutral position in the frontal plane [16–19].

The main function of the terminal stance phase is to maintain the body's center of gravity at such a height relative to the surface at which the potential energy level will be optimal for the transfer of the contralateral limb (Fig. 1) [16–19].

The preswing phase is the most complex of all phases of the gait cycle. The beginning of this phase corresponds to the contact of the opposite limb with the surface, and the end corresponds to the lifting of the toes of the ipsilateral leg from the floor. The transfer of body weight to the contralateral limb results in a decrease in the flexion torque of the ankle ground reaction force of the limb being assessed, which causes a decrease in the activity of plantar flexors.

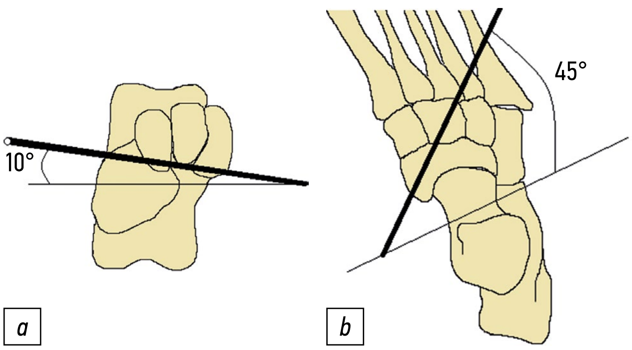

Fig. 2. Axis of movement of the first ray: *a*, horizontal plane; *b*, frontal plane (Michaud T. Foot orthosis. Baltimore, 1993; [55], with modifications)

The continued eccentric contraction of the plantar flexors with heel lift and forward movement of the shin at the beginning of the preswing phase is subsequently replaced by concentric contraction of the gastrocnemius and soleus, leading to plantar flexion of the foot up to 15°. Such active extension of the foot creates a powerful impulse (up to 3.7 W/kg·m for an adult), or pushoff, which is necessary for transferring the limb. The kinematic characteristics of the preswing phase of the assessed limb are maximum inversion in the subtalar joint, knee joint flexion of 40°, reduction of the ipsilateral side of the pelvis to 5°, and anterior pelvic tilt to 10° and 5° of its external rotation. External rotation of the lower leg, thigh, and pelvis is at maximum at the end of this phase. The main function of the preswing phase is to prepare for the limb transfer [16–19].

The importance of the normal functioning of the forefoot components is emphasized by the load that these anatomical structures experience during the final phases of the stance period. Thus, I.A. Stokes et al. [20] revealed that in the preswing phase, the first toe is affected by 40% of the body weight, and the resulting reaction forces from the support surface, creating compression on the articular surfaces, is approximately 600 N. W.C. Hutton and M. Dhanendran [21] concluded that the forces influencing the first metatarsophalangeal joint are nearly comparable to the body weight (Fig. 1).

Functionally, the phases of terminal support and preswing are called “third rocker” [16–19].

First ray of the foot

The first ray is the functional unit of the foot and consists of the first metatarsal and medial cuneiform bones, which are connected by strong ligaments [22]. These anatomical formations are identified as a separate unit in the work by J.H. Hicks [23] and used to describe the functional anatomy of the anterior medial arch of the foot. Subsequently, the first ray became the object of study by scientists examining the etiopathogenesis of hallux valgus deformity of the first toe.

The resulting axis of movement of the first ray of the foot was described by J.H. Hicks using cadaver materials in 1954 [23]. This axis is directed from the tuberosity of the scaphoid to the base of the third metatarsal bone. The axis tilt is 45° from the frontal and sagittal planes and 10° from the horizontal plane (Fig. 2).

The movement of the first ray of the foot is uniaxial and in three planes. This movement is performed in the direction of plantoflexion and dorsoflexion in the sagittal plane, abduction and adduction in the horizontal plane, and supination and pronation in the frontal plane. Plantoflexion of the first ray is combined with its pronation and abduction, i.e., eversion, and dorsoflexion is combined with supination and adduction, i.e., inversion (Fig. 3) [24–31].

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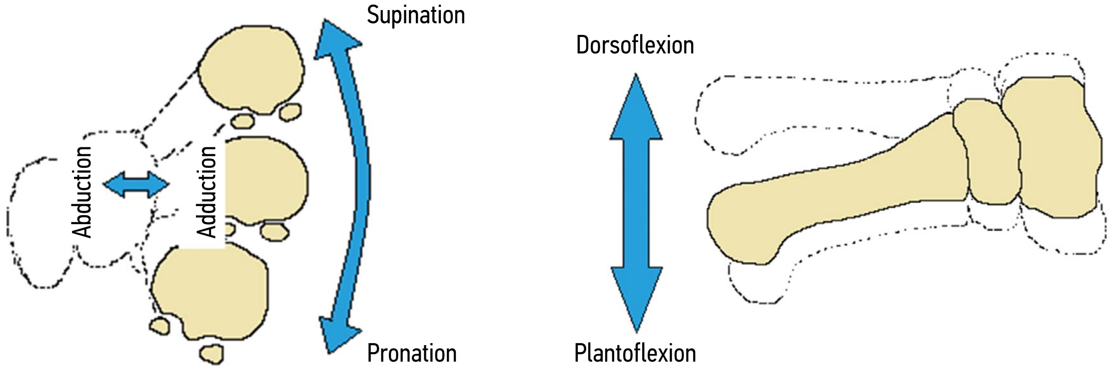

Fig. 3. Movement of the first ray: *a*, horizontal plane; *b*, sagittal plane

T.E. Sgarlato [28], M.L. Root [32], and A. Wanivenhaus and M. Pretterklieber [33] examined the range of motion of the first ray. The range of motion of the first ray in the sagittal plane is greater than in the horizontal plane, and with dorsoflexion, the range of motion in the horizontal plane increases.

Only a few studies have attempted to measure midfoot joint motion. Thus, T. Ouzounian and M. Shereff [34] determined that the range of motion in the direction of dorsoflexion and plantoflexion in the medial naviculocuneiform joint averages 2.3° (0.7° to 8.7°) and 3.5° (1.9° to 5.3°) in the first cuneo-metatarsal joint, respectively. Supination–pronation movements in the medial naviculocuneiform joint average 7.3° (3.5° to 9.9°) and 1.5° (0 to 2.6°) in the first cuneo-metatarsal joint, respectively.

L.L. Oldenbrook and C.E. Smith [35] studied the movement of the first metatarsal head under axial load. They concluded that the movement of the first ray in the sagittal plane is greater than that of other metatarsals, whereas the eversion of the first ray is less than that of metatarsal bones II–V.

First metatarsophalangeal joint

The formation of the first metatarsophalangeal joint involves four articular surfaces surrounded by a common articular capsule. Since the joint is condylar, movements are possible in both the sagittal and horizontal planes. The main movement occurs in the sagittal plane, whereas rotational movements are passive and provide only some additional mobility to the main phalanx of the first toe [22, 36].

The function of the first metatarsophalangeal joint is determined not only by its bone elements but also by the structure of soft tissues. These structures form a “hammock,” which consists of a concave surface of the proximal phalanx with multiple soft tissue attachments [36].

Sesamoid bones, the articular capsule with ligament and muscle-tendon fibers woven into it, form the so-called joint cushion. The anatomy of this joint is determined by the concentration of soft tissue attachments to the proximal phalanx with the formation of the so-called hammock, inside which the head of the first metatarsal bone rotates. This anatomical feature was described by Heatherington as a “dynamic acetabulum” [37].

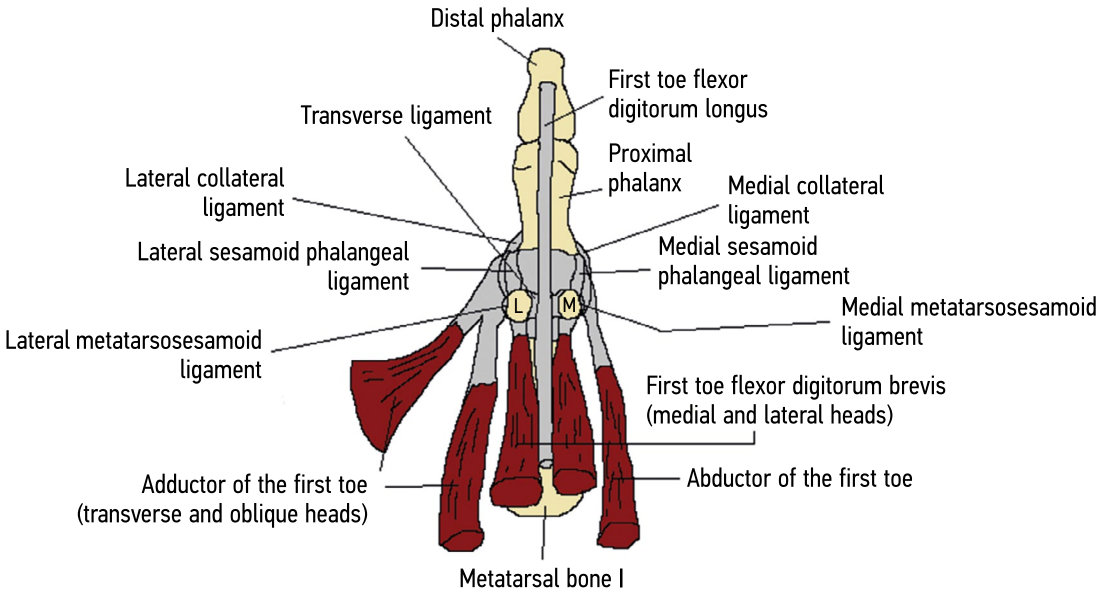

Fig. 4. Sesamoid apparatus of the foot. L, lateral sesamoid bone; M, medial sesamoid bone

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The medial and lateral collateral ligaments, sesamoid phalangeal ligaments, metatarsosesamoid ligaments, and transverse intersesamoid ligament form a triangle with three ligaments on each side of the joint, tightly woven into the joint capsule (Fig. 4) [38]. Greater stabilization is facilitated by the transverse intersesamoid ligament, which is located across the sesamoid bones, forming a strap or belt and thereby limiting the divergence of the sesamoid bones under load.

This complex of supporting structures, or "hammock," provides not only movement of the first metatarsal head but also medial–lateral stability of the joint. With pathology such as *hallux valgus*, the "hammock" shifts in the frontal plane because of the pronation of the first toe. In this case, the medial shoulder of the "hammock," together with the medial sesamoid bone, which provides lateral stabilization of the head of the first metatarsal bone, shifts plantarly, creating the prerequisites for the medial deviation of the first metatarsal bone [22].

This joint has two axes of motion and two degrees of freedom. The horizontal axis characterizes the movement in the sagittal plane as flexion and extension, whereas the vertical axis in the horizontal plane characterizes abduction and adduction.

The first metatarsophalangeal joint belongs to the so-called hinge-sliding joints. The nature of the movement is determined by the degree of dorsoflexion of the first toe. Hinge or rotational movements occur in the first 20–30° of extension. Subsequently, the first ray of the foot flexes, displacing the horizontal axis of the joint rotation, which is localized in the head of the metatarsal bone, dorsally and proximally. This process during walking leads to the sliding movements of the first ray down and back (Fig. 5) [22]. Data on the nature and amplitude of movement of the first toe in the horizontal plane around the vertical axis are not presented in the literature.

V.L. Heatherington [37] studied movements at the first metatarsophalangeal joint using a load simulating walking and identified four centers of rotation. Their projection onto the head of the metatarsal bone forms an arch-like figure. The first center is located near the articular surface and supports the onset of rotational movement. The next two rotation centers, located closer to the center of the head, determine the tangential sliding movements along the articular surface. This sliding movement was believed to occur simultaneously with plantoflexion of the first ray. The final center of rotation is located dorsally on the metatarsal head, with a vector passing through the proximal phalanx of the first toe. In this position, at the end of the movement, compressive forces arise in the joint (Fig. 5).

On the contrary, M.J. Shereff et al. [39] described only the compressive and sliding nature of the movements in the first metatarsophalangeal joint.

Some studies have analyzed the range of motion of the sesamoid bones relative to the head of the first metatarsal bone. Thus, Shereff [39] noted a displacement of the sesamoid bones during extension at the first metatarsophalangeal joint from 10 to 12 mm. However, V.L. Heatherington et al. [37] did not reveal any significant movement of the sesamoid bones.

The literature describes many variations in the range of motion of the first metatarsophalangeal joint in the sagittal plane. According to various authors, the range of motion in the first metatarsophalangeal joint required for normal walking ranges from 27° to 90° [18, 28, 36, 37, 40–47]. The movements of the first toe in the horizontal plane

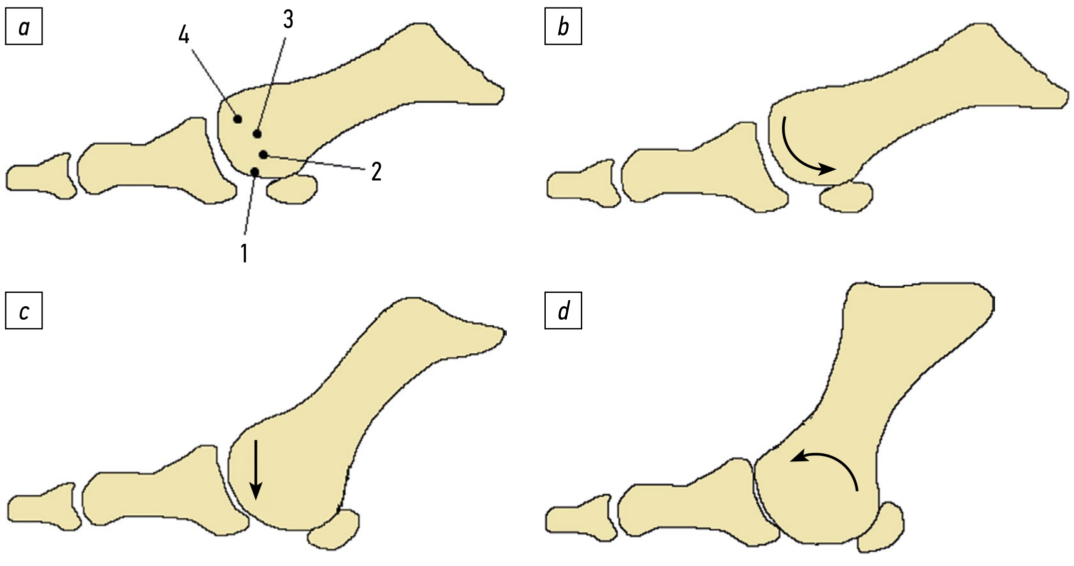

Fig. 5. Projection of the centers of rotation of the first metatarsophalangeal joint (*a*) (1–4), rotational movement of the head of the first metatarsal bone (*b*), sliding movement of the head of the metatarsal bone (*c*), and compressive movement of the first metatarsal bone head (*d*) (Ronald L. Valmassy. 1994, [22], with modifications)

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were accepted by humans from anthropoid apes because of evolutionary changes associated with upright walking, has no functional significance and, according to R.L. Valmassy [22], and is practically not controlled by active muscle work.

Assessment of the localization of the vector of reaction forces on various parts of the foot during normal walking

An important issue in the study of the biomechanics of the foot and lower limb is the determination of the center of pressure on the contacting part of the foot during normal walking. The data obtained, together with kinematic and kinetic studies, indicators of electromyographic research, and gait analysis, formed the idea of the normal or pathological function of the locomotor apparatus. The center of pressure is the projection of the reaction forces of the support or the vector of the body, which is a vector quantity and directed in the opposite direction from the surface according to Newton's third law. This vector quantity indicates the direction of movement in the joints and the work of lower limb muscles (Fig. 6) [16–19].

In some works [48], the localization of the center of pressure is normally limited to the first metatarsophalangeal joint and the first toe in the final phases of the stance phase. Research results regarding the projection of the center of pressure on the forefoot are unclear. Thus, some authors claim that this projection is normally located under the head of the first metatarsal bone [49, 50], whereas others mentioned a projection under the head of the second [51] or third metatarsal bone [52]. In the work of J. Hughes [53], such a projection zone is the first toe.

Movements of the elements of the first metatarsophalangeal joint and the first ray of the foot when walking

During the swing period, the toes are extended at the metatarsophalangeal joints because of the active contraction of the toe extensor muscles. This position provides the necessary lift of the foot during the swing and continues until the foot contacts the surface [16]. Then, from the initial contact phase to the midstance phase, the toes flex passively, reaching a mid-position in the metatarsophalangeal joints [16].

During the terminal stance and preswing phases, the projection of the vector of the ground reaction forces moves forward from the rotation axes of the metatarsophalangeal joints, creating an extension torque and conditions for passive toe extension [25].

The short and long flexors and abductor and adductor of the first toe are responsible for the active stabilization

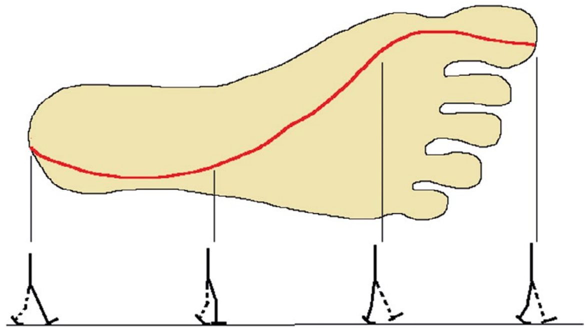

Fig. 6. Projection of the center of pressure on the foot during normal walking according to A.K. Mishra [48]. The solid line is the evaluated limb, and the dotted line is the contralateral limb (Ronald L. Valmassy. 1994, [22], with modifications)

of the first toe in the metatarsophalangeal joint in the third rocker phases [43].

The long flexor of the first toe is active in the midstance phase, phase of terminal support, and preswing phase. This multi-joint muscle also controls ankle joint dorsoflexion and foot eversion in the subtalar joint, which determines its activity throughout the midstance phase.

The flexor brevis is activated at the end of the midstance phase and implements its function through the sesamoid bones. The sesamoid bones, located under the head of the first metatarsal bone, function as a block for this muscle, determining the angle of attachment of its tendon, and the magnitude of the flexion torque lever relative to the axis of rotation of the first metatarsophalangeal joint [54, 55].

When the heel is lifted and the body moves forward in the terminal stance and preswing phases, the projection of the ground reaction forces shifts anteriorly from the axis of rotation of the first metatarsophalangeal joint. This increases the extensor torque lever and causes passive first toe extension. Passive extension in the first metatarsophalangeal joint is related to the fact that the axis of the muscle belly of the short and long flexors of the first toe is located at an angle relative to the place of attachment of their tendons to the proximal and distal phalanges of the first toe, respectively. In addition, in this position, both muscles have an effective lever arm for flexing the first toe, or limit the extension of the first toe in the metatarsophalangeal joint (Fig. 7*b*). When the heel is positioned on the surface and due to the lack of first toe extension, the toe flexor muscles are not activated. In this case, the traction of the long and short flexors of the first toe, without a block effect when the sesamoid bones are located under the head of the metatarsal bone, will stabilize the first toe against the metatarsal bone head, but not against the surface (Fig. 7*a*) [22].

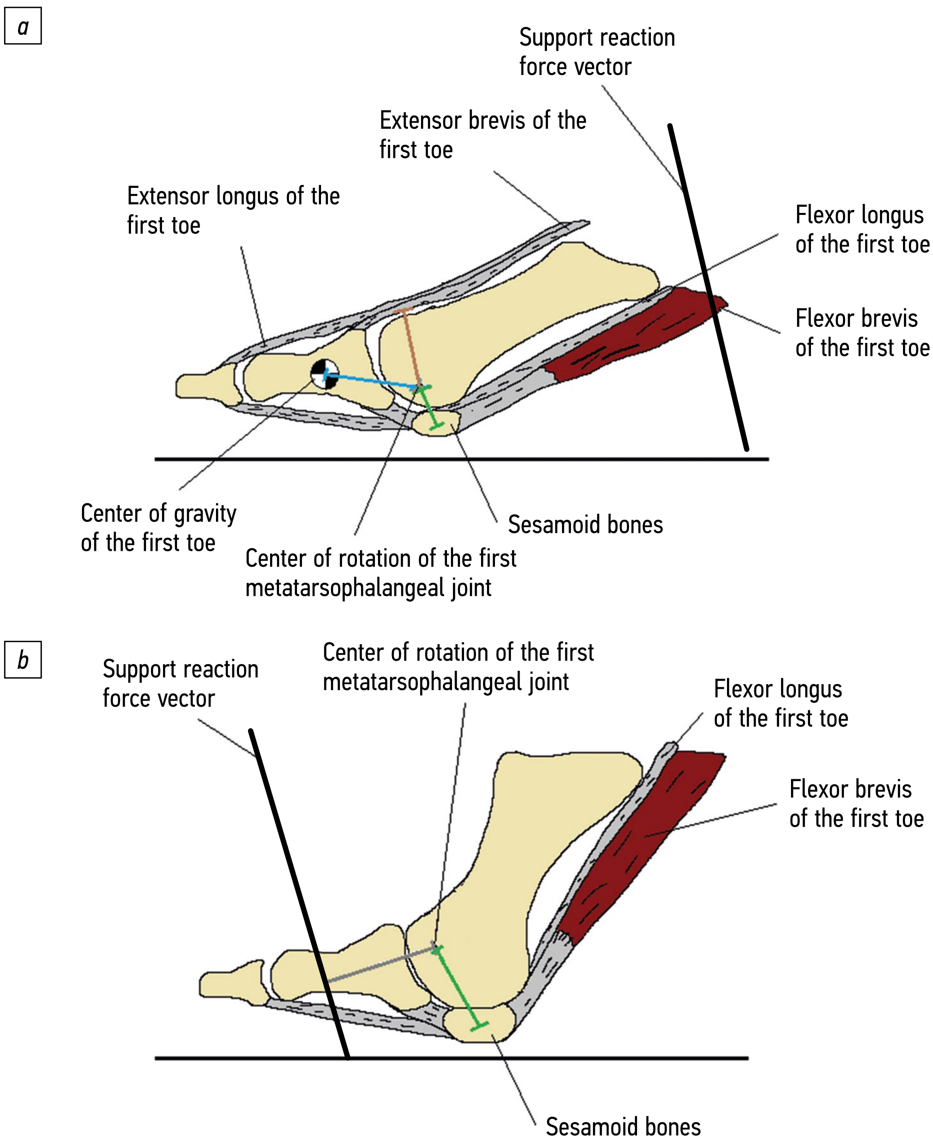

Fig. 7. Function of the short and long flexors and short and long extensors of the first toe in the midstance phase (*a*). During this phase, the projection of the ground reaction force vector is located behind the first metatarsophalangeal joint and does not have any effect on it. The localization of the first toe on the surface neutralizes the flexion torque of the center of gravity of the first toe and determines the stabilizing effect of the flexors and extensors of the first toe of the proximal phalanx of the first toe against the head of the first metatarsal bone. The function of the long flexor of the first toe, short flexor of the first toe, and sesamoid apparatus in the third rocker phase (*b*). The vector of ground reaction forces is located anterior to the first metatarsophalangeal joint, creating an effective extension torque lever. The sesamoid bones and the displacement of the center of rotation of the first metatarsophalangeal joint to the anterosuperior parts of the head increase the flexion torque of the short flexor of the first toe, which provides active counteraction to the passive extensor action of the ground reaction forces. The blue line indicates the torque lever arm of the center of gravity of the first toe, the green line indicates the torque lever arm of the short extensor of the first toe, the brown line indicates the torque lever arm of the extensor muscles of the first toe, and the gray line indicates the torque lever arm of the ground reaction forces

The abductor and adductor of the first toe provide stability to the first metatarsophalangeal joint in the horizontal plane. H. Kelikian et al. [36] suggested that this joint is stabilized by the influence of the adductor and abductor of the first toe on the “hammock” structures. Similarly, M.A. MacConaill [56] hypothesized that the traction of the dorsal plantar and medial–lateral hammock fibers maintains the stability of the metatarsal head as it flexes during gait. The development of *hallux valgus* of the first toe may be associated with the dysfunction of the components of the sesamoid apparatus. This pathological condition leads to excessive traction of the “hammock” lateral fibers and lateral displacement of the adductor of the first toe, followed by the progressive lateral displacement of the first toe in the horizontal plane and deformity.

An important aspect is determining the function of the first ray of the foot when walking. Thus, the extension of the first toe in the metatarsophalangeal joint in the terminal support and preswing phases is accompanied by the flexion of the first ray of the foot. This movement of the first ray after heel lift-off is necessary for the extension of the first toe at the metatarsophalangeal joint during these phases of the gait cycle [16, 22].

According to M.L. Root [31], the flexion of the first ray is one of the main determinants of the normal functioning of the foot in the third rocker phases, along with the muscles that ensure the stability of the first toe and the first ray of the foot, work of the sesamoid apparatus, and inversion of the calcaneus in the subtalar joint.

During the initial contact, the first ray of the foot is in maximum extension due to the tibialis anterior traction. Then, under the control of this muscle, the first ray bends until the foot completely touches the surface.

In the loading response phase, the shock-absorbing function of the foot is implemented because of valgus of the hindfoot, midfoot pronation and extension, and forefoot supination. Hindfoot valgus in this stance phase is caused by the eversion of the calcaneus and internal rotation of the bones of the lower leg with the talus fixed in the ankle mortice, which is in adduction, flexion, and supination. This relationship in the subtalar joint determines the parallel arrangement of the axes of the talonavicular and calcaneocuboid joints, which increases the mobility of Chopart's joint, leading to midfoot pronation and extension. In this phase, the forefoot is supinated relative to the calcaneus, mainly due to extension, adduction, and inversion of the first ray (Fig. 8*a, b*).

In the midstance phase, the body is transferred over a single support limb. In this phase, the bones of the lower leg with the talus fixed in the ankle mortice move forward in the ankle joint, performing ankle joint flexion, and rotate outward in the subtalar joint, leading to abduction, extension, and pronation of the talus. The calcaneus moves in the direction of inversion, reducing the hindfoot valgus. Calcaneal inversion will result in the loss of alignment between the talonavicular and calcaneocuboid joints, reducing the mobility of Chopart's joint, supinating and flexing the midfoot. Forefoot supination relative to the hindfoot decreases because of the onset of first ray flexion.

In the terminal stance and preswing phases, calcaneal inversion reaches its maximum values, which leads to the "blocking" of movements in Chopart's joint and extreme midfoot supination and flexion. In addition, in these phases, the first ray continues to flex passively to ensure

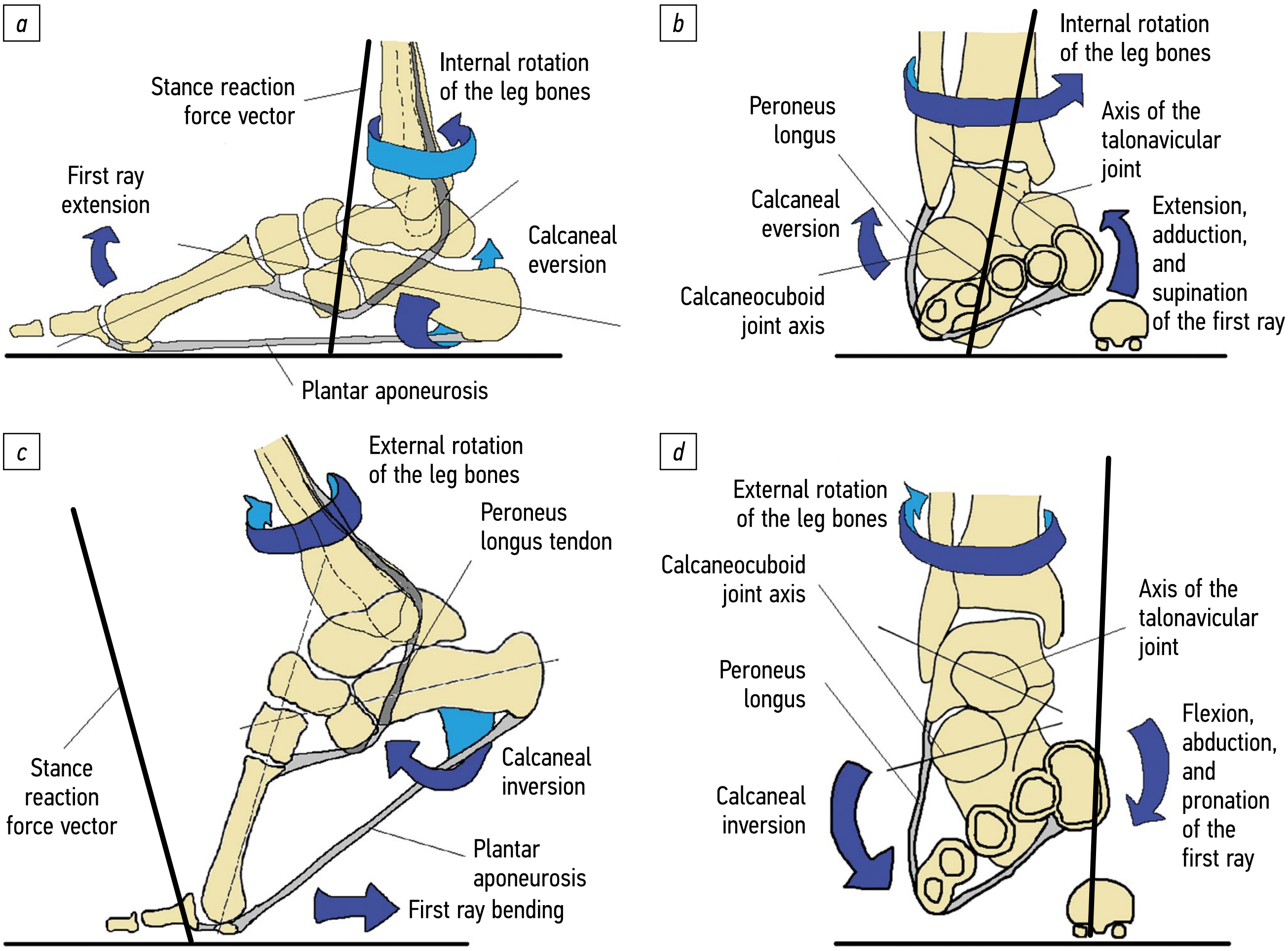

Fig. 8. Position of the first ray and foot in the loading response and initial midstance phases in the sagittal and frontal planes (*a*, *b*). Position of the first ray and foot in terminal stance and preswing phases in the sagittal and frontal planes (*c*, *d*). Explanations are given in the text

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the extension at the first metatarsophalangeal joint until it reaches the end of the maximum permissible range of motion (Fig. 8*c, d*).

According to S.R. Kravitz et al., for sufficient extension of the first toe during walking, flexion of the first ray of 10° is necessary. The flexion of the first ray reduces the degree of compression in the first metatarsophalangeal joint during walking [57].

According to Heatherington, the average angle of extension of the first toe before the beginning of flexion of the first ray is 34° [37]. Moreover, during the terminal stance and preswing phases, the first toe is in an extension position of 50–60° relative to the longitudinal axis of the first metatarsal bone [16, 22].

M.L. Root [31] argued that the ability of the first ray to flex during forward movement of the body over the first toe is ensured by the inverted position of the calcaneus in the subtalar joint and, as a consequence, the "locked" Chopart's joint. In this case, midfoot supination and flexion lead to an increase in the height of the transverse arch and form an effective torque arm of the peroneus longus tendon (Fig. 8*d*). Under such biomechanical conditions, the peroneus longus muscle in these phases is an active flexor and stabilizer of the first ray relative to the midfoot and the first metatarsal bone against the arm of the lever of the extensor torque of the ground reaction forces (Fig. 8*b*). In other words, it limits the dorsiflexion of the first ray of the foot.

However, according to S.R. Kravitz et al. [57], the lever arm of the peroneus longus as a flexor of the first ray is insufficient. The main function of the peroneus longus is

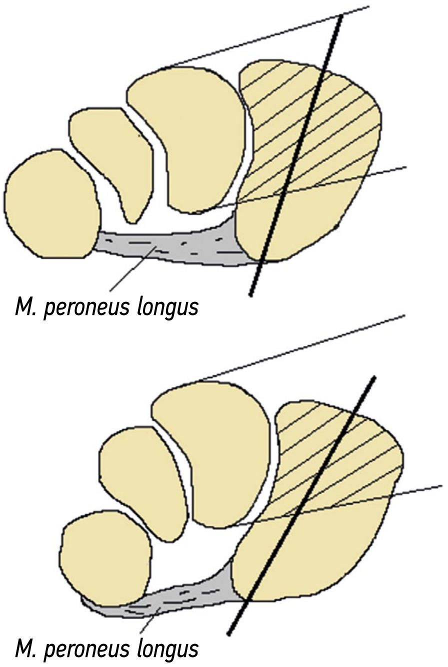

Fig. 9. Mechanism for blocking the first ray of the foot. See text for explanations

an active control of the transfer of the projection of ground reaction forces in the terminal stance and preswing phases from the lateral to the medial part of the foot, when not only an extension but also a lateral torque occurs in the midfoot against a rigidly fixed head of the metatarsal bone I (Fig. 8*b–d*) [57].

Some authors [23, 57] have considered the action of the abductor of the first toe as a flexor of the first ray. Together with the sesamoid bones, during the third rocker phase, the abductor of the first toe is in a good position for the development of an effective flexion arm of the first ray [57].

Assessing extension in the first metatarsophalangeal joint with movement in other joints of the lower limb in the sagittal plane, J. Perry [16] concluded that normally during the "third rocker" phase, this movement of the first toe is accompanied by 35° knee joint flexion and 20° ankle joint plantoflexion.

Forefoot locking mechanism

Functionally, the foot is considered a kind of energy absorption adapter during initial contact with the surface and as a rigid lever necessary to implement an effective pushoff in the final stance phase [58].

The talonavicular and calcaneocuboid joints make up Chopart's joint, or midtarsal joint, which can lock to provide stability. This mechanism is critical to the transition of the foot from a mobile adapter that absorbs the energy of the initial contact to a rigid lever during pushoff. The position of the heel in the frontal plane plays an important role in this locking mechanism. The axes of the calcaneocuboid and talonavicular joints intersect when the calcaneus is inverted, forming a thrust between the calcaneus and talus, which limits movement (Fig. 8*d*) [59–62]. Some studies have presented a quantitative assessment of the function of the locking mechanism of the midtarsal joint in different forefoot and hindfoot positions [62, 63]. A similar mechanism has been described for the knee joint [64].

C.H. Johnson et al. [63] established on cadaver material in that the first ray can rotate in the frontal plane. The tension of the *m. peroneus longus* leads to the eversion of the first ray to a greater extent than to its flexion. This eversional position of the first ray has a blocking effect on the forefoot because of the special shape of the structure of the intermetatarsal joint of the first and second metatarsal bones. The medial surface of the base of the second metatarsal is convex, whereas the lateral surface of the first metatarsal is concave. When the first metatarsal bone is rotated in the direction of eversion, the movements of the first metatarsal bone in the sagittal plane are blocked (Fig. 9) [65]. The activation of the *m. peroneus longus* during these phases of the gait cycle blocks the midfoot joints participating in the formation of a rigid lever of the foot [31].

DISCUSSION

The leading biomechanical event in the terminal stance and preswing phases of the stance phase is dorsoflexion of the first toe in the first metatarsophalangeal joint, which is impossible without flexion of the first ray. This movement, which at first glance does not present any difficulties, is possible because of successive complex multiplanar interactions in the multisegmental system of the entire lower limb. In this case, the role of motor control from the central nervous system consists in maintaining sufficient height and minimizing fluctuations in the center of gravity of the body and ensuring the correct localization of the projection of the center of gravity to the area of the first metatarsophalangeal joint and the first toe.

The localization of the projection of the body's center of gravity onto the area of support determines the work of the muscles and the nature of foot joint movement. Normally, by the pushoff beginning, the projection of the center of gravity onto the support area shifts forward from the axis of the subtalar joint in the sagittal plane and tends to its axis in the horizontal plane, i.e., from the outer part of the foot in the direction of the first metatarsophalangeal joint [16, 22]. This movement of the center of gravity is accompanied by calcaneal inversion and midfoot supination, and is controlled by the *m. peroneus longus*.

The described range of motion of the first ray and its components is presented without indicating the joint or joints where the motion occurs. This may be due to difficulties in recording angular displacements between the short bones of the foot.

An important question is determining the mechanism that ensures the flexion of the first ray of the foot when walking and the nature of this movement, i.e., if it occurs in the joints of the medial column or it is associated with a change in its spatial position relative to the structures of the foot and lower limb.

J.H. Hicks [66] considered the flexion of the first ray relative to the calcaneus, activated by a windlass mechanism. The tension of the plantar aponeurosis caused by the extension at the metatarsophalangeal joints will result in calcaneal inversion and positional flexion of the first ray (Fig. 8). In contrast, in a pilot study by R.D. Phillips et al. [67], a correlation was revealed between the extension of the first toe and flexion in the first naviculocuneiform joint. The authors noted that the first 20° of the extension in the first metatarsophalangeal joint is not accompanied by any flexion of the first ray; however, with further movement, the plantar flexion of the first metatarsal bone relative to the hindfoot will occur in 1° for every 3° of the extension in the first metatarsophalangeal joint. Thus, the flexion of the first ray reduces the amount of ankle joint plantoflexion and reduces knee and hip joint flexion, maintaining the center of mass of the body at the required height.

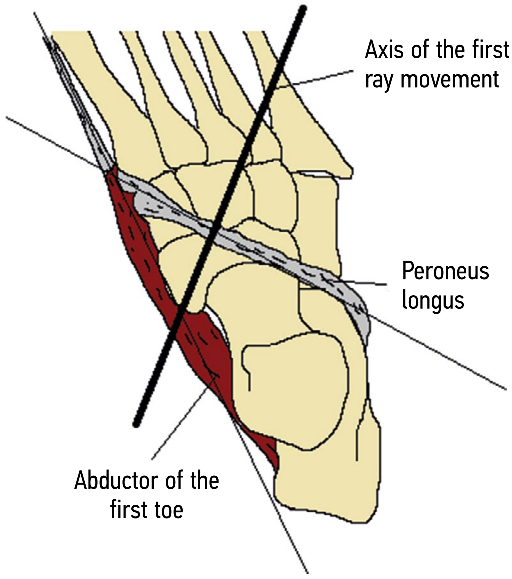

Fig. 10. Location of the axes of the first toe abductor and peroneus longus relative to the resulting axis of movement of the first ray of the foot. See text for explanations

In turn, S.R. Kravitz supported the opinion of Hice (unpublished data) that the main phalanx of the first toe in the final phases of the stance period exerts a retrograde effect on the head of the first metatarsophalangeal bone, pushing it posteriorly and causing first ray flexion [57].

The function of the first toe abductor as an active flexor of the first ray is quite debatable. This muscle is located at an angle of 45° to the axis of the first ray, creating an effective lever for its flexion. However, the axis of the peroneus longus tendon is at an angle of 90° to the axis of movement of the first ray, which makes its flexion torque more effective (Fig. 10). Moreover, the short flexor of the first toe, attached to the plantar–medial surface of the cuboid bone and lateral sphenoid bone, is considered the flexor of the first ray [22, 57].

The position of the ankle, knee, and hip joints during the terminal stance and preswing phases of the stance period can influence the plantoflexion of the foot first ray during walking. However, these studies were conducted with the range of motion assessed in the sagittal plane [16]. The rotational movements in the hip and knee joints, performed in the horizontal plane and affecting the calcaneal position in the subtalar joint when supporting the surface and, therefore, the first ray plantoflexion, have not been studied. We have not found such works in the literature.

CONCLUSION

Normal functioning of the forefoot, first metatarsophalangeal joint, and first ray of the foot is one of the most important elements of human gait. Further studies of the function of these components of the foot, intersegmental and intrasegmental interactions in the foot joints, and the entire lower limb will help in determining disease etiopathogenesis.

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Author contributions. *V.V. Umnov* developed the main idea of the study and performed staged editing of the article text; *V.A. Novikov* developed the study design, searched and analyzed the literary sources, and performed staged editing; *D.S. Zharkov* created the study design, performed final editing, and wrote the article text; *D.V. Umnov* searched and analyzed the literary sources.

All authors made significant contributions to the study and preparation of the article, and they read and approved the final version before its publication.

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