3

Biomechanics

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Hallux valgus seems to be the hallmark of forefoot deformities. Its occurrence in the modern society has been estimated to be between one-tenth,[1] one-sixth,[2] and one-third[3,4] of the population. It has also been noted to occur at least twice as often in women as in men.[5] It has on several occasions been referred to as the "hallux valgus complex",[3,6] meaning that when it occurs, it is associated with a multitude of other symptoms or deformities of the forefoot. These include calluses under the forefoot, metatarsalgia, splayfoot, flatfoot, plantar fascitis, and hammer toes. Thus, in the study of hallux valgus one often must discuss all these other deformities.

Hallux valgus seems to be a deformity that was uncommon until the wearing of fully enclosed shoes and boots. Early Greek and Roman sculptures are devoid of this deformity. Meyer,[7] in comparing skeletal remains, reported that early Pecos Indians, an unshod population, had a lower hallux abductus angle than shod Yugoslav peasants from a similar time period. The earliest mention of such deformity in the literature was in the eighteenth century. During the nineteenth century, its occurrence and etiology were discussed many times. During the nineteenth and twentieth centuries, several expeditions by scientists into the undeveloped areas of the world, notably Africa and the islands of the Pacific, noted that hallux valgus is only rarely seen in those who do not wear shoes. Hoffmann[8] reported that the foot is fan shaped, with the hallux in a straight line in natives of the Philippines and in central Africans, and that the digits become compressed toward one another when one starts wearing shoes (Fig. 3-1). Maclennan[9] noted 3.2 percent of the men and 8.3 percent women over the age of 30 years in New Guinea highlands had evidence of hallux valgus, while fewer of the lowland natives had the deformity. Kalcev[10] reported 17 percent of males and 15 percent of females in Madagascar showed hallux abductus (by Meyer's line) greater than 10° versus 50 percent of European woman. James[11] reported on the very straight inner border of the feet in Solomon Island natives, seeing no cases of hallux valgus, and also noting the much stronger intrinsic foot muscles compared to Europeans. Haines and McDougall[12] reported that one adult Burmese woman started to develop bunions after wearing shoes only 3 months. Engle and Morton[13] reported very few foot problems exist in the shoeless African native population, and that the orthopedic surgeon would have very little work with these people. Jeliffe and Humphreys[14] reported that almost no orthopedic deformities were seen in the 464 barefoot Nigerian soldiers they examined.

Others also note that hallux valgus rarely occurs in those who only wear sandals and other types of shoe gear that keep the first and second digits separated. Sim-fook and Hodgson[4] reported that hallux valgus was almost 20 times more common in Chinese who wore shoes than in the barefooted population who lived on boats. Kato reported that the deformity is not present in any of the ancient Japanese footprints. Morioka[15] reported that it does not occur in the forestry workers who wear *jikatabi*, a rubber shoe that keeps the big toe separated from the other toes, but has become common in a new generation who wear western-style logging boots. Thus Japan has noted a great increase in the occurrence of this deformity during the last half of the twentieth century as its citizens have adopted western footwear over the traditional Japanese footwear.[16]

From the fact that the deformity occurs mostly in the shoe-wearing population, and that women tend to

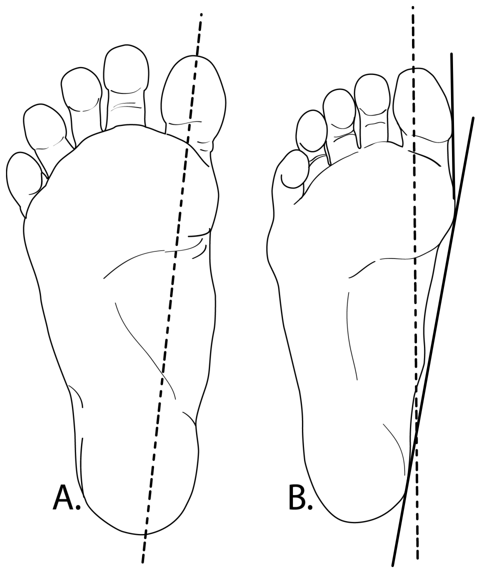


Fig. 3-1. (A) A foot that has never worn shoes. (B) A normal foot that has worn shoes. Feet that have never worn shoes are commonly found to have the digits in alignment with their respective metatarsals, giving the foot a fan shape. Normal feet that wear shoes are commonly found to have the digits in alignment with the longitudinal axis of the rearfoot, thus giving the foot a sarcophagus shape. (From Hoffman,[164]).

wear pointed-toed, high-heeled shoes, the most obvious conclusion would be and has been that wearing misfitted, pointed-toed shoes is the primary etiology in initiating hallux valgus.[17-22] Porter[23] noted the importance of good shoes in treating people with hallux valgus and suggested that surgery not be performed if the patient is unwilling to wear the proper shoes. Knowles[24] argued that shoes alone could correct hallux valgus by having a special shoe constructed for a patient with hallux valgus that fanned out at the toes to allow space for the toe to adduct back to alignment with the first metatarsal. After 3.5 years the patient showed some improvement on one side and little improvement on the other. Barnett also performed a limited study on nine experimental subjects and eight controls over 2 to 3.5 years, showing that some feet did decrease the hallux abductus angle in special shoes with extra toe room, while some still showed a mild increase in the deformity even when wearing the special shoes; women were more prone to increase the deformity and less likely to decrease it with the special shoes than men.[25] Shine also partly confirmed these conclusions by examining 88 percent of the feet in St. Helena, where approximately 50 percent of the population wears shoes on a voluntary basis but men and women wear very much the same types of shoes. He found that bunions were much more frequent in the shoe-wearers, and that the severity of the bunions increased with the increase in the number of years that the person had worn shoes. However, even when both sexes wore similar sensible, rounded shoes there was still a marked increase in the occurrence of hallux valgus in females compared to males.[26] Craigmile[27] did show, in 1953, that a group of children who were kept properly fit for shoes, with changes every 3 to 4 months, did have decreased incidence of hallux valgus than was observed in the general population of children. She also noted that hallux valgus incidence was higher in the group of children who wore shoes with pointed toes and/or no support in the arch.[27]

The facts are then that hallux valgus is a deformity seen almost exclusively in the shoe-wearing population. However, many other observations have been made to show that many other factors must be considered in deciding the exact etiology of hallux valgus. Ely,[28] for example, pointed out that if the wearing of ill-fitting, pointed-toed shoes alone were the cause of hallux valgus, it would mean that a direct correlation should be found between the degree of poor fit or the degree of the pointedness and the degree of hallux valgus. Mensor[29] noted that such cannot be shown, and in fact those in the lower working class, who wore less fashionable shoes, suffered more. Wilkins[30] also noted that the feet of poor men and women are more susceptible to deformity than the feet of those who are well off. Narrow, pointed, high-heeled shoes are worn by both classes of women while in neither class do men wear such shoes. The footwear of the poor, however, is of poorer quality with less variation in fitting and in poorer repair. Heath[31] reported that an examination of various shoe lasts showed that many of the pointed-toe shoe lasts actually gave more freedom for the toes than the rounded-toe shoe lasts. Many individuals who wear pointed-toed shoes do not develop hallux valgus, and there are also many who wear "sensible" shoes who do develop hallux valgus.[32] There are also those who develop hallux valgus on only one foot, although wearing the same type of shoe on both feet, and there are also those who develop hallux valgus who wear no shoes.[33,34] Barnicot and Hardy[35] showed a significant difference in the hallux abductus angles between European and Nigerian feet, but found no difference between Nigerians who wore shoes and those who did not. In addition, Gottschalk et al.[36] found that white feet developed hallux valgus twice as commonly as black feet in South Africa although both groups wore shoes. Others have found that the wearing of arch supports inside a shoe can give significant relief or even prevent surgery on bunions,[37,38] while others have proposed that arch supports should be worn postoperatively to prevent recurrence of the deformity.[39] Hawkins and Mitchell[40] thought that shoes could only produce bunions if a metatarsus primus (adductus) deformity was already present. Thus, in studying the etiology of hallux valgus, factors must be found that in themselves could produce hallux valgus but are much more likely to produce the deformity when shoes are worn.

Some individuals have considered heredity and the congenital nature of the disease.[41] There are a few isolated reports of babies being born with hallux abducto valgus[42]; however, none of these report large bunions accompanying the hallux deformity. More than 50 percent of those who do have bunions report that the deformity was noticed before the age of 20, usually during the pubescent years.[43] Hicks'[44] concluded that if a woman can reach the age of 20 with a hallux abductus angle of less than 10° it is very unlikely that she would ever develop hallux valgus. Sandelin[45] noted that hereditary influence was manifested in 54 percent of hallux valgus cases, and Johnston,[46] in examining one family tree, concluded that hallux valgus was transmitted as an autosomal dominant trait with incomplete penetrance. Jordon and Brodsky[47] proposed that the role of foot wear was only secondary, serving to aggravate an already existing mild deformity. Wallace[48] reported in an examination of 224 nine-year-olds that all those with evidence of hallux valgus showed either a positive family history or had a mobile first metatarsal that was plantar-flexed below the level of the others. Metcalf[49] reported that 80 percent of those with hallux valgus had abnormal pronation in their feet and that anterior arch plates gave relief to a large percentage. Hardy and Clapham[50] also showed that there was a high correlation between hallux valgus and pronation of the foot, plantar calluses, and limitation of mobility in the transverse tarsal joint. Pronation and broken arches, both the medial arch and/or the anterior metatarsal arch, has also been named by many others to be a major factor in the development of the deformity.[51-54] McNerney and Johnston,[55] as well as Carl et al.,[56] have demonstrated greater generalized ligamentous laxity in the joints in those with hallux valgus than those who did not have it. Other factors that have also been shown to be at least part of the etiology include rheumatoid arthritis,[57-59] amputation of the second toe, neurologic disorders, abnormal joint obliquity in the first metatarsocuneiform joint,[60] excessive transverse plane roundness of the first metatarsal head,[61] and the presence of accessory bones between the bases of the first and second metatarsal.[62,63]

Hallux valgus is combined with a medial or dorsomedial prominence of the first metatarsophalangeal joint that is commonly called a "bunion." The degree of hallux valgus was originally measured by the acute angle formed by Meyer's line (Fig. 3.1 B), which is a line that is tangent to the medial side of the heel and to the medial side of the first metatarsal head, and a second line that is tangent to the two most medial points along the hallux. After the advent and widespread use of x-ray examinations in evaluating deformities, the hallux valgus angle has since become defined by a line that bisects the shaft of the first metatarsal and a line that bisects the shaft of the first proximal phalanx. Because there is a continuum of values in the population, various numbers have been used over the years to try to define the boundary between the normal hallux valgus and the abnormal hallux valgus value. Some have based this value on those who suffer from bunions and those who do not; however, there is considerable overlap in the hallux valgus angles between these two groups. Some have based this value on the average value seen in the unshod natives of the world, which is between 0° and 5°; however, this places most of those who wear shoes in the abnormal category. Others have tried to find the average value in the general population, but because of the number who do suffer from bunions, this shifts the normal curve to an increased value. Thus normal values have been considered to be at any point between 0° and 30° (Fig. 3-2). Although no absolute value can be established that unequivocally defines the boundary between normal and abnormal, it has generally become accepted

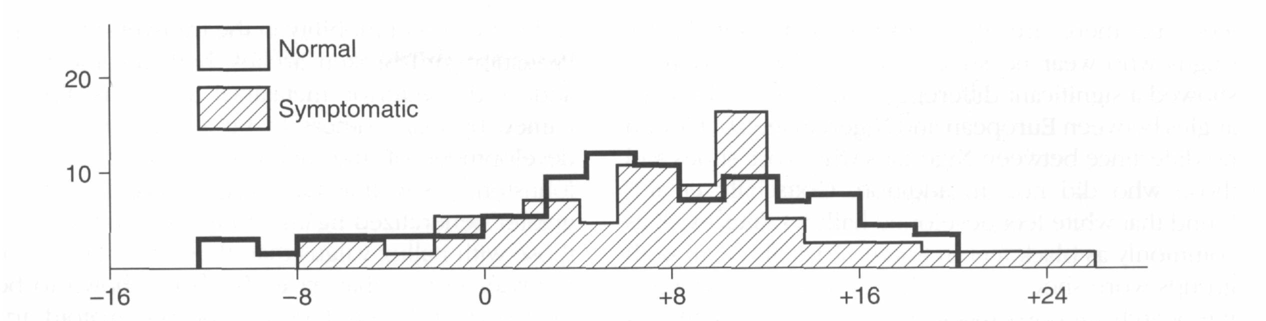


Fig. 3-2. Although the normal hallux valgus angle is considered to be about 15°, there are individuals who have a larger angle than this with no signs or symptoms of hallux valgus, and there are those with a smaller angle who do have symptomatic hallux valgus. This histogram by Barnicot and Hardy compares the hallux valgus angle of those with normal feet and those with symptomatic hallux valgus. (From Barnicot and Hardy,[35] with permission.)

that if the hallux angle becomes more than 15°,[60,64] the patient may be considered to have some degree of abnormality. The decision to treat any abnormality is then based on whether the patient is having symptoms or is likely to develop symptoms.

ANATOMY AND FUNCTION OF THE NORMAL FIRST RAY

The basic functional anatomy must be first considered in discussing the development of hallux valgus deformity. The first metatarsophalangeal joint is actually two joints with a common joint capsule and interrelated muscles and ligaments (Fig. 3-3). The distal portion is a partial ball-and-socket type morphology between the first metatarsal and the proximal phalanx, while the second portion is a rounded groove between the plantar first metatarsal and the dorsal surface of two sesamoids. These sesamoids are connected by vertical fibers to the sides of the first metatarsal head and by horizontal fibers to the plantar base of the proximal phalanx. In addition, oblique fibers run from the epicondyles of the metatarsal head to the plantar sides of the base of the proximal phalanx. It is now considered that the sesamoids are ossification centers that develop within the plantar plate under the first metatarsal head.[65] They are connected by very dense fibers that are akin to the tissue found in the lesser plantar plates, forming what is commonly called the intersesamoidal ligament. The lateral sesamoid also is connected by very strong fibers to the plantar plate under the second metatarsal head by the transverse intermetatarsal ligament. The strength of these connections, which is determined by both the strength of the fiber and the geometry between fibers, means that the distance between the sesamoids and the plantar plate of the second metatarsal head is almost always seen to remain constant.[66,67] Finally, there are attachments of the sesamoids to the deep vertical fibers of the plantar fascia that are pulled taut when the sesamoids are pulled forward. When the plantar fascia is tightened up, all the fibers of the forefoot are also tightened, which increases the resistance of the soft tissues to compression.

In addition to their ligamentous attachments, the sesamoids are also strongly attached to several tendons. The flexor hallucis brevis has origins from the cuboid, the lateral cuneiform, the medial septum, and the metatarsal extension of the posterior tibial tendon. It divides distally and invests both sesamoids. The abductor hallucis blends its lateral fibers with the medial tendon of the flexor brevis so that a portion of its fibers helps invest the medial sesamoid[68] (Fig. 3-4). The oblique head of the adductor hallucis is much smaller in man than in lower primates.[69] It arises from the peroneal sheath and the bases of the central three metatarsals, and blends its medial fibers with the lateral head of the flexor hallucis brevis, thus helping in the investment of the lateral sesamoid. Further distally its lateral fibers join those of the transverse head of the adductor hallucis to send their fibers directly to

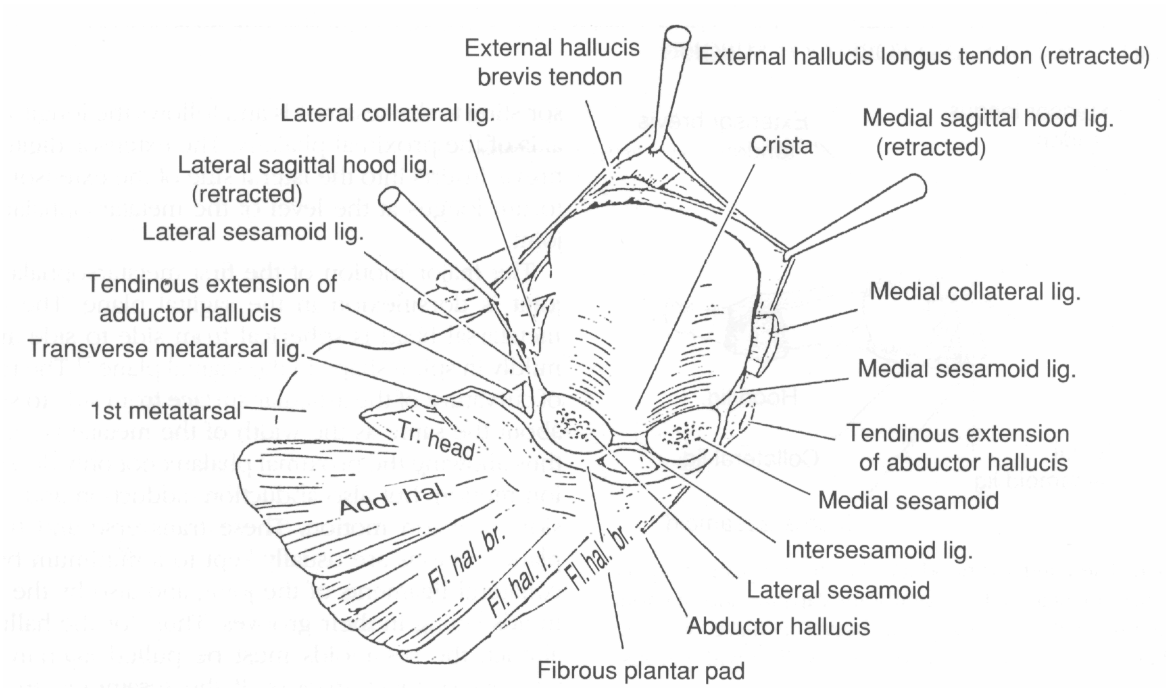


Fig. 3-3. Normal anatomy around the first metatarsophalangeal joint. The first metatarsophalangeal joint is a socket composed of the sesamoids, the base of the proximal phalanx, and the surrounding ligaments, with the first metatarsal only attached by ligaments inserting into the medial and lateral epicondyles of the first metatarsal. (From Alvarez et al.,[108] with permission.)

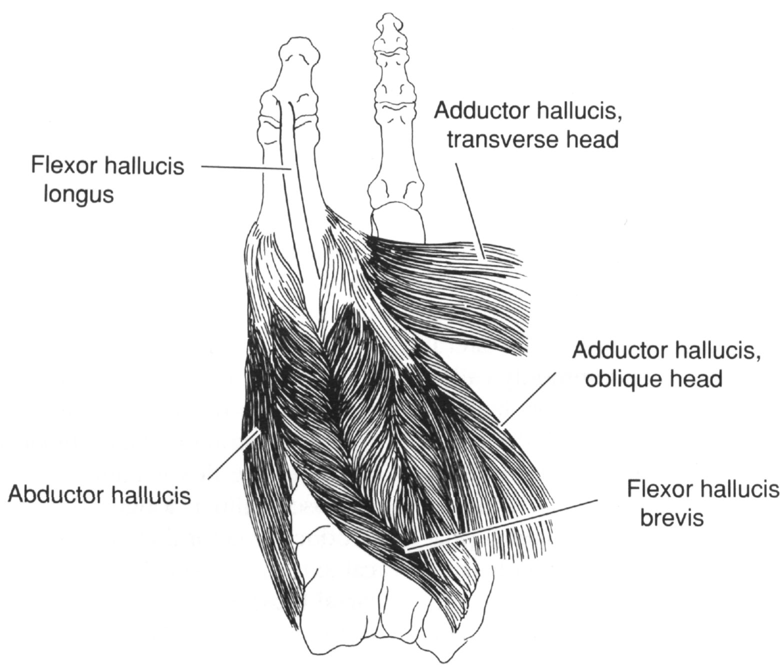


Fig. 3-4. Orientation of the normal musculature around the first metatarsophalangeal joint. (From McCarthy and Grode,[66])

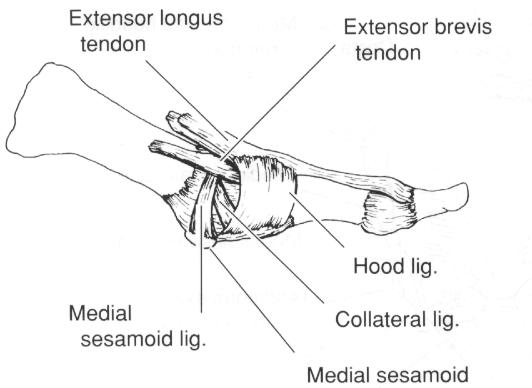


Fig. 3-5. The extensor hood attaches to the plantar aspect of the first metatarsophalangeal joint capsule and anchors the extensor hallucis longus and brevis in place over the dorsal aspect. (From Raines and McDougall,[112])

the plantar base of the proximal phalanx.[70] Thus, because of the ligamentous and tendinous attachments of the sesamoids to the proximal phalanx, the distance between the sesamoids and the proximal phalanx will also attempt to remain constant, and if one looks at the strength of the ligamentous and fibrous attachments of the sesamoids, one finds the weakest attachments of the sesamoids to be those with the metatarsal head.

Several other tendons pass the first metatarsophalangeal joint (Fig. 3-5). The transverse head of the adductor hallucis is a small muscle originating from the transverse intermetatarsal ligament segments and forming a conjoined tendon with the oblique head of the adductor hallucis to proceed directly to the lateral base of the proximal phalanx. It is commonly called the transversus pedis muscle. The flexor hallucis longus muscle runs in a groove just under the intersesamoidal ligament and is held firmly in place within this groove. It then proceeds forward to lie within a groove under the entire length of the proximal phalanx before attaching to the base of the distal phalanx. The extensor hallucis longus runs over the dorsal surface of the first metatarsophalangeal joint, and while it was commonly thought of as being free of the metatarsophalangeal joint such that it made a beeline to its attachment at the base of the distal phalanx, it is now realized that it is anchored by the fibers of the extensor sling to the sesamoids and follows the longitudinal axis of the proximal phalanx. The extensor digitorum brevis inserts into the lateral side of the extensor digitorum longus at the level of the metatarsophalangeal joint.

The major motion of the first metatarsophalangeal joint is dorsiflexion in the sagittal plane. The distal metatarsal head is spherical from side to side and is mildly in spiral shape in the sagittal plane.[71] The radius of curvature of the articular surface from side to side is about the same as the width of the metatarsal head, [72] thus allowing the proximal phalanx not only dorsiflexion motion, but also abduction—adduction and inversion-eversion motion. These transverse and frontal plane motions are usually kept to a minimum by the collateral ligaments of the joint, and also by the sesamoids riding in their grooves. Thus, for the hallux to abduct, the sesamoids must be pulled laterally part way out of their grooves. If the sesamoids are well compressed in their grooves, the joint is much harder to abduct than if there is no compression between the sesamoids and their grooves. When the hallux everts, the plantar-lateral sesamoid ligament tightens from compression of the lateral sesamoid in its groove, and the medial sesamoid ligament slackens. If the toe is in a maximally dorsiflexed position, both ligaments are already tightened and the range of eversion of the toe is decreased.

No one has fully studied the transverse plane motion in the first metatarsophalangeal joint; however, it is assumed to occur around the center of curvature of the metatarsal head when viewed on the transverse plane, which means that this vertical axis would pass directly between the sesamoids. If this is the case, then the pull of the abductor hallucis in a plantar-medial direction is combined with an equal pull of the adductor hallucis in a plantar-lateral direction (Fig. 3-6). A pull of both heads of the flexor hallucis brevis would produce a straight plantar flexion of the joint as would a pull of the flexor hallucis longus and a pull of the extensor hallucis longus; this occurs because all three produce a vector that passes directly through the vertical axis of motion. The more rounded the first metatarsal head is, the closer the vertical axis would lie to the joint surface. Thus, small displacements medially or laterally in the round first metatarsal head will produce greater angular changes than in the flatter first metatarsal head. It also means that greater transverse angular torque is more likely to develop with a

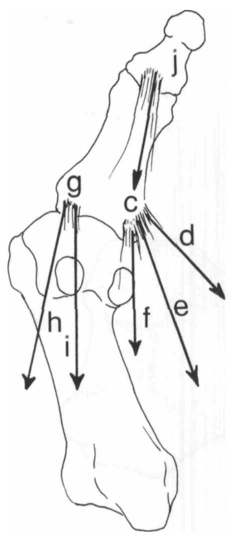


Fig. 3-6. The pull of the plantar instrinsic muscles on the proximal phalanx when the joint is in abducted position, showing that there is a significant overload of the muscles to the lateral side, c, insertion of lateral conjoined tendon; d, transverse head of adductor hallucis; e, oblique head of adductor hallucis; f, lateral tendon of flexor hallucis brevis; g, insertion of medial conjoined tendon; h, abductor hallucis; i, medial tendon of flexor hallucis brevis; j, flexor hallucis longus. (From Dykyj,[116])

given amount of pull of either the adductor or abductor hallucis muscle in the rounded first metatarsal head.

The first metarsophalangeal joint, therefore, must be considered as a modified socket with the base of the proximal plalanx and the sesamoids, with their ligamentous attachments forming a cup that is well anchored together, and the first metatarsal floating within, very loosely attached to the cup structures. Because of the spiral shape of the first metatarsal head in the sagittal plane, the axis of dorsiflexion-plantar flexion does not stay fixed. When the first metatarsophalangeal joint dorsiflexes in a non-weight-bearing situation, the axis of motion moves in a circular pattern from center to distal, then dorsal and finally distal-proximal, producing a sliding action of the joint surface.[73,74] However, when the foot is in a weight-bearing situation the hallux stays fixed and the entire metatarsal lifts and rotates around an axis that moves from the central surface in an arc proximally and superiorly[75] (Fig. 3-7). Because of the sliding action of the hallux on the phalanx, if the first metatarsal rotated solely around this axis it would also roll forward, thus producing an abnormal compression between the proxi-

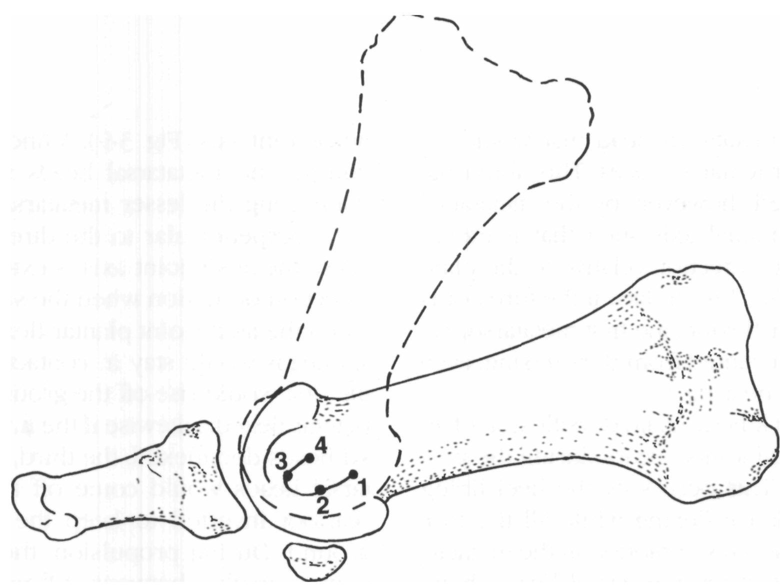


Fig. 3-7. The axis of the first metatarsophalangeal joint in open kinetic chain moves in a semicircular pattern as the proximal phalanx moves from full plantar flexion to full dorsiflexion. Note that if the first metatarsal moved around this axis in closed kinetic chain, the first metatarsal head would lose contact with the ground (dotted line). (From Shereff,[74])

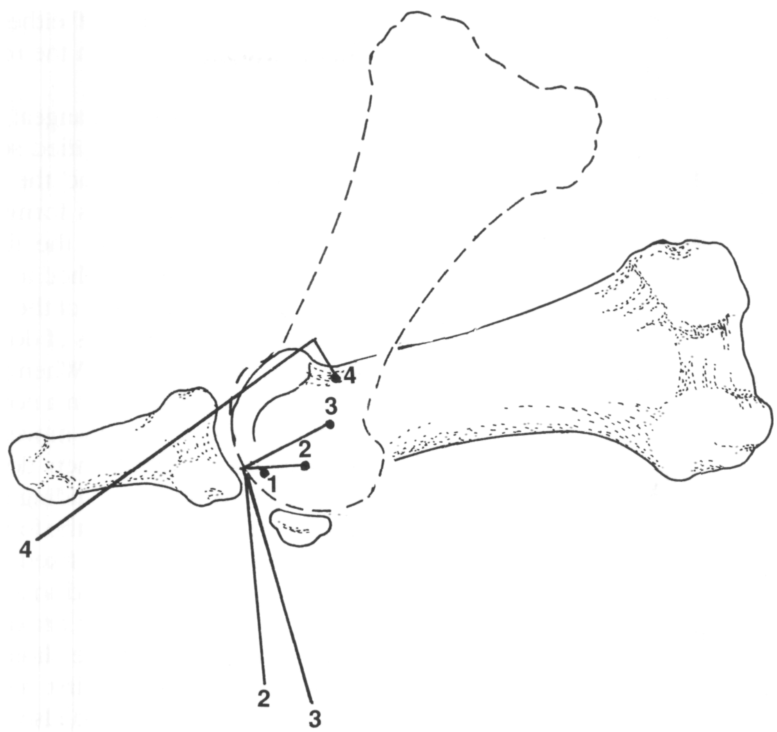


Fig. 3-8. By combining a plantar flexion motion of the first metatarsal with the dorsiflexion of the first metatarsophalangeal joint, the first metatarsal rotates around a moving axis, as determined by Hetherington et al. (From Hetherington et al.,[75])

mal phalanx and the metatarsal head that would induce damage to the articular surfaces. This abnormal compression is avoided, however, by the metatarsal rotating around a proximal axis such that it moves proximally, in a plantar direction relative to the plantar plane of the foot (Fig. 3-8). In fact, if the forefoot is prevented from plantar-flexing, the first metatarsophalangeal joint will be prevented from dorsiflexing, even when it is non-weight-bearing.[76]

As was noted, closed kinetic chain dorsiflexion of all the metatarsophalangeal joints occurs during the propulsive phase of gait. This occurs by the heel lifting and the ankle joint plantar-flexing while all the foot bones rotate around the axes of motion in the metatarsal heads. If one looks at the metatarsal heads, however, a fairly straight line is noted that connects the central portions of the second, third, fourth, and fifth metatarsal heads. This line is almost parallel with the ankle joint axis (Fig. 3-9). A line that connects the first and second metatarsal heads is oblique to the line connecting the lesser metatarsal heads and is essentially perpendicular to the direction of motion.[77] Because the ankle joint axis is externally directed to the direction of motion when the subtalar joint is neutral, when the ankle joint plantar-flexes, the lesser metatarsal heads would stay in contact with the ground and the first would rise off the ground unless the first also plantar flexed. Likewise if the first and second metatarsal heads dorsiflexed, the third, fourth, and fifth metatarsal heads would come off the ground unless the rearfoot inverted to keep the lateral heads on the ground. During propulsion, the metatarsophalangeal joints dorsiflex between 40° and 60°[78]; however the ankle joint only plantar-flexes about half as much. It would thus seem apparent that for all the metatarsophalangeal joints to stay on the ground through a nor-

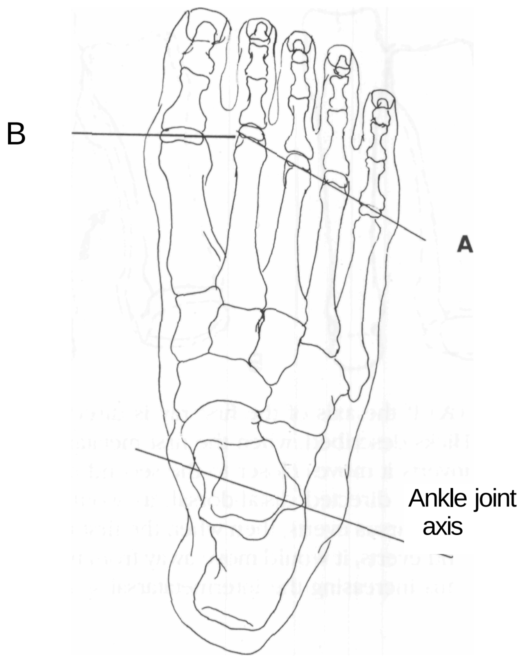


Fig. 3-9- During propulsion the lesser metatarsophalangeal joints rotate around an axis that lies along line. A, while the first metatarsophalangeal joint rotates around line B. To keep all five metatarsal heads against the ground, the ankle joint must plantar-flex around an axis that is almost parallel with line A while the subtalar joint supinates and the first metarsal plantar-flexes to keep the first metatarsal head on the ground. (From Bojsen-Moller,[133])

mal degree of propulsion, both these mechanisms must occur; that is, the ankle joint must plantar flex, the first metatarsal must plantar flex, and the rearfoot must supinate.

It was noted by many early authors that one of the most obvious changes between the primate and human foot was in the shape and motion of the first metatarsal.[79] The evolutionary trend has been for the first metatarsal to become a major weight-bearing bone and the lesser metatarsals to become less significant for weight-bearing.[80] The primate has a first metatarsal that is much shorter than in the human, with the first metatarsocuneiform joint facing medially, approximately 30 degrees more than in humans,[81] so that its motion is very much like the thumb, being used in apposition with the lesser metatarsals.[82,83] The adductor hallucis is a very large fan-shaped muscle originating along the entire shaft of the second metatarsal, while in man it has shrunk to two small heads.[69] In man the first metatarsal has become much longer, about the same length as the second metatarsal, and the first metatarsocuneiform is directed much more anteriorly. Its range of motion has become much smaller, and it does not function as an opposer of the second metatarsal. The adductor hallucis has become much reduced in size, while the flexor hallucis brevis and the abductor hallucis have increased.

The motion of the first metatarsal proximally was described first by Hicks[84]; he described the combined motion of the first metatarsal and first cuneiform around one single axis that was called the axis of the first ray. This axis proceeded from the navicular tuberosity, slightly inferior to the base of the third metatarsal and slightly superior. This would mean that the axis would be approximately 45° angulated laterally with the frontal plane and slightly angulated upward (Fig. 3-10). Motion around this type of axis would pro-

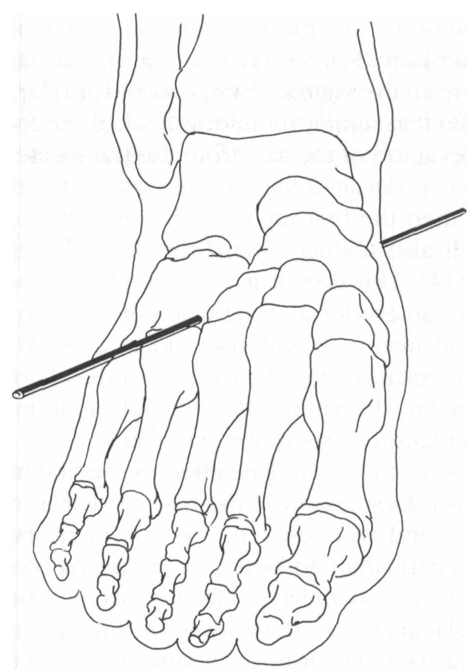


Fig. 3-10. The first-ray axis was determined by Hicks to be almost 45° to the frontal and sagittal planes and slightly tilted downward as it proceeded from proximal to distal. (From Hicks,[84])

duce an equal number of degrees in the sagittal and frontal planes and just a slight angular motion on the transverse plane. Because of the length of the head from the axis, motion in the sagittal and transverse planes would exhibit relatively large excursions, while frontal plane motion would exhibit a relatively small excursion. Ebisui[85] divided the motion of the first into a motion that was first mainly a sagittal plane motion of the first metatarsocuneiform joint, followed by a rolling motion at the first naviculcuneiform and the first-second intercuneiform joint such that the first metatarsal would first dorsiflex and then the first cuneiform would invert. Kelso et al.[86] further studied the motion of the first ray relative to the fixed second ray and noted that the dorsiflexion of the first ray relative to the second ray also produced an inversion motion, while plantar flexion produced an eversion motion. The average sagittal plane motion was 12.4 mm with the average frontal plane motion of 8.2°. Although Kelso et al. did not compare degree motions, the ratio of frontal to sagittal plane motion did vary significantly, from 0.27 to 1.41. This indicates that there is significant variance between individuals in the angular deviation of the first-ray axis from the sagittal plane. If such interindividual variety exists in the deviation of the axis from the sagittal plane, it would also be logical to assume that significant interindividual variety exists in the deviation of the axis from the transverse plane. If the axis is deviated from posterodorsal to anterior-plantar, then the first ray when it dorsiflexes and inverts will also abduct toward the second metatarsal (Fig. 3-11A). However if it is deviated from postero-plantar to anterodorsal, then when the first ray dorsiflexes and inverts, it will also adduct away from the second metatarsal (Fig. 3-11B). No studies have been performed to determine what type of variation in the axis orientation exists in the population.

Because of the multiplane effect of the first metatarsal motion dorsiflexion of the first metatarsal relative to the second will result in the first metatarsal also inverting and either adducting or abducting according to the direction of the axis. Likewise, as the first metatarsophalangeal joint dorsiflexes during gait and the first metatarsal plantar-flexes relative to the second, to allow the ankle joint to plantar-flex the first metatarsal everts relative to the second and will move closer or further away from the second according to the direction of the axis. Thus, closed kinetic chain dorsiflexion of the joint in which the hallux is held stable produces a frontal plane rotation within the joint such that there is a relative inversion of the first proximal phalanx on the metatarsal head[87] as well as possibly some degree of transverse plane motion.

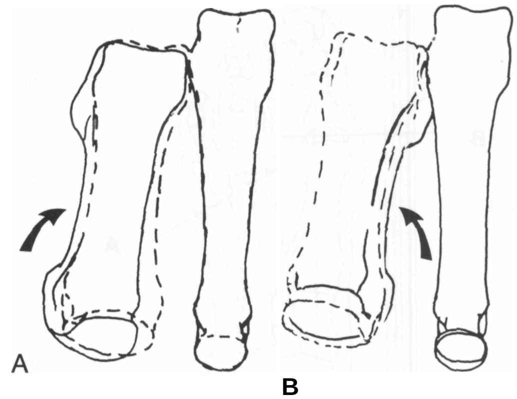


Fig. 3-11. (A) If the axis of the first ray is directed distal-plantar, as Hicks described, when the first metatarsal dorsiflexes and inverts it moves closer to the second metatarsal. (B) If the axis is directed distal-dorsal, as would happen when the lesser tarsus everts, then when the first metatarsal dorsiflexes and everts, it would move away from the second metatarsal, thus increasing the intermetatarsal spacing.

A further study of the transverse and frontal plane motion within the first metatarsophalangeal joint can be attained by studying the effect of the rearfoot motions on the forefoot. D'Amico and Schuster[88] and Oldenbrook and Smith[89] both demonstrated that as the rearfoot pronates and the calcaneus becomes everted to the ground the metatarsals also will evert relative to the ground, and when the calcaneus becomes inverted to the ground all the metatarsals will invert to the ground. It is logical then to assume that when the forefoot is everted to the ground, the axis of the first ray will become more everted causing it to point in a more dorsal direction, and when the forefoot is inverted to the ground, the axis of the first ray will become more inverted causing it to point in a more plantar direction.

With eversion of the forefoot, the first and second metatarsals experience greater pressure against the ground, which places a supination force on the longitudinal axis of the midtarsal joint and a dorsiflexion force on the first and second metatarsals. Because the midtarsal joint is further from the forefoot than the axis of the first ray, it may be assumed upward force against the plantar surface of the first metatarsal will place a stronger supination torque around the midtarsal joint than around the first-ray axis and thus the midtarsal joint will tend to supinate until the forefoot is on the ground.[85] Hicks demonstrated the small range of motion that is present around the longitudinal axis of the midtarsal joint compared to the other tarsal joints. Phillips and Phillips[90] also demonstrated that to keep the midtarsal joint fully pronated the forefoot would have to exponentially evert more than the rearfoot as the subtalar joint pronated. Thus with every degree that the rearfoot everts and pronates, the midtarsal joint must invert a greater amount to compensate. In the average foot, the end of midtarsal joint supination around the long axis can be expected when the calcaneus everts more than 4°-6°, although there are great variances in the population. Once the midtarsal joint has reached the end of its range of motion to compensate for rearfoot eversion, therefore, additional eversion of the rearfoot will be compensated by dosiflexion of the first ray. As the first ray dorsiflexes it also inverts relative to the second metatarsal, although it may remain somewhat everted to the floor.

As was noted previously, when the metatarsophalangeal joint dorsiflexes in closed kinetic chain, the rearfoot inverts as do all the metatarsals; however, because the first metatarsal is plantar-flexing, it is everting relative to the second metatarsal and thus the first metatarsal inverts less than the other metatarsals during propulsion. The purpose of propulsion is to generate force against the ground to propel the center of mass forward and onto the opposite leg. Thus, ground reaction forces not only must exceed body weight to lift the body mass upward before it begins its descent down for the opposite foot, but they must also generate a forward shear to push the body mass forward, and a slight medial shear to allow the smooth transfer of weight onto the opposite limb.

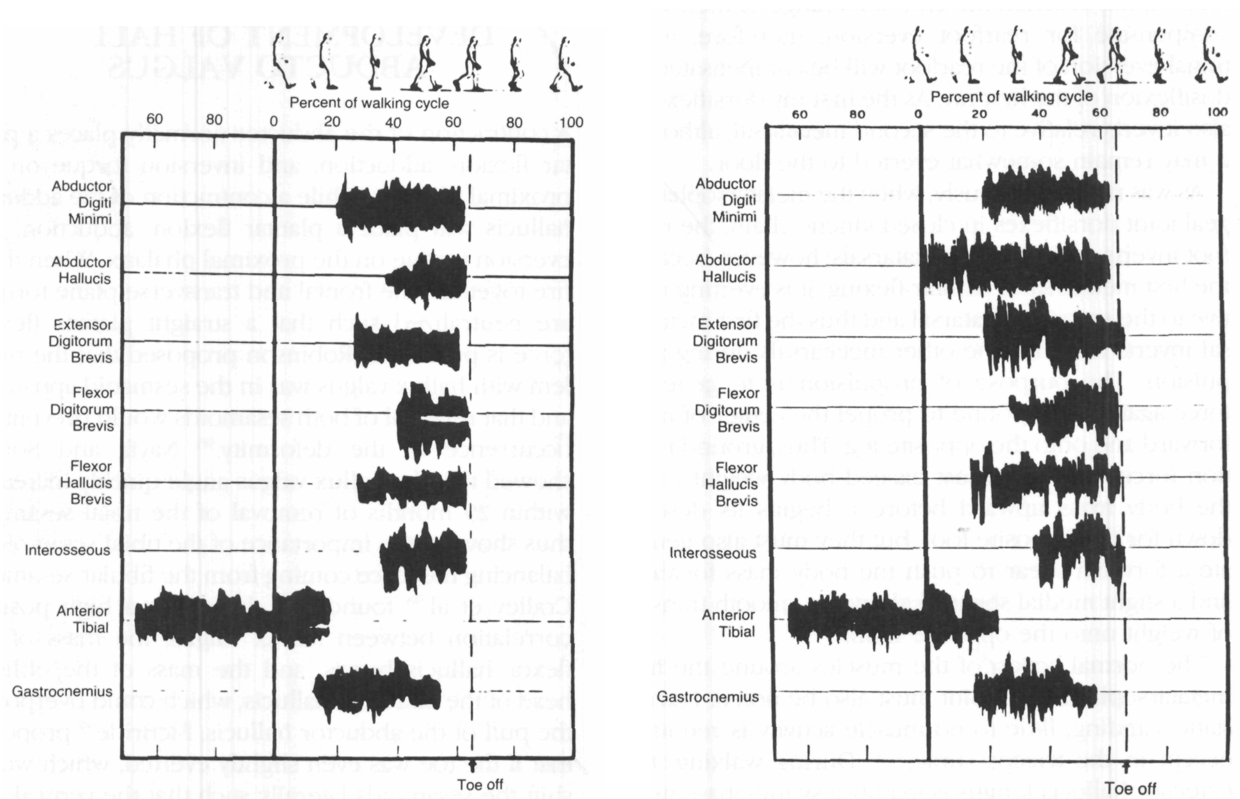
The normal action of the muscles around the first metatarsophalangeal joint must also be noted. During static standing, little to no muscle activity is required except in the triceps surae.[91,92] During walking, the extensor hallucis longus is mainly a swing-phase muscle, beginning its contraction in the last portion of propulsion and ending its contraction before the entire forefoot has contacted the ground. Its basic function is to produce a straight open kinetic chain dorsiflexion of the metatarsophalangeal joint. The other muscles that cross the metatarsophalangeal joint are all stance-phase muscles. The flexor digitorum longus begins firing during contact period and the flexor hallucis brevis with the abductor and adductor begin firing before the heel comes off the ground.[93,94] It is the firing of all these plantar muscles that stabilizes the hallux against the ground so that the metatarsal may roll forward without the hallux also rolling forward. When the peak of backward force against the ground is reached, the long plantar muscles relax and the extensor hallucis longus contracts, allowing the metatarsal head to lift from the ground and the foot to start rolling forward onto the end of the toe. When the anterior tibial starts firing then the entire foot dorsiflexes at the ankle joint, clearing the toe from the ground.[95]

DEVELOPMENT OF HALLUX ABDUCTO VALGUS

A contraction of the abductor normally places a plantar flexion, adduction, and inversion torque on the proximal phalanx, while a contraction of the adductor hallucis will place a plantar flexion, abduction, and eversion torque on the proximal phalanx. When these fire together, the frontal and transverse plane torques are neutralized such that a straight plantar flexion force is produced. Robinson proposed that the problem with hallux valgus was in the sesamoid apparatus, and that removal of both sesamoids would prevent the occurrence of the deformity.[96] Nayfa and Sorto[97] showed that the hallux valgus angle quickly increased within 29 months of removal of the tibial sesamoid, thus showing the importance of the tibial sesamoid in balancing the force coming from the fibular sesamoid. Cralley et al.[98] found that there was a high positive correlation between hallux valgus, the mass of the flexor hallucis brevis, and the mass of the oblique head of the adductor hallucis, which could overpower the pull of the abductor hallucis. McBride[99] proposed that if the toe was even slightly everted, which would shift the sesamoids laterally such that the vertical axis around which transverse plane motion occurs would not pass directly between the sesamoids, then a transverse plane torque would be produced when their corresponding muscles both contract with equal force, which would allow the hallux to move to the lateral side of the first metatarsal. The relationship of the longitudinal axis around which frontal plane motion occurs has never been investigated, but it has been hypothesized that if the tibial sesamoid moves directly plantar to the first metatarsal that the abductor hallucis loses all its inversion and adduction torque and cannot counteract any eversion and abduction torque produced by the adductor hallucis. Hallux valgus would thus ensue whether or not the patient wore shoes.[100]

Schubert[101] attributed the abnormal pull of the abductor hallucis when learning to walk—when pronation was present—as the greatest contributing factor in the development of hallux valgus. As was noted, the abductor and adductor hallucis contract during late midstance and through propulsion. However, in the highly pronated foot these muscles begin contracting almost from the beginning of heel contact.[102,103] (Fig. 3-12). This means that these muscles begin contracting before the first metatarsal can contact the ground, while it is still dorsiflexed and inverted relative to the second metatarsal, and abduction and adduction balance around the first metatarsal is lost in the early stages of contact.

All cases of hallux valgus demonstrate a sesamoid apparatus that has moved laterally under the first metatarsophalangeal joint (Fig. 3-13). In moving laterally, the medial sesamoidal and medial collateral ligaments become stretched; microtears develop that subsequently heal in a thickened but more disorganized manner, thus making the medial ligaments weaker than the lateral ones.[104] The medial sesamoid moves closer to the vertical axis while the lateral sesamoid



B

Fig. 3-12. (A) Electromyograph (EMG) activity of foot muscles in the normal foot. (B) EMG activity of foot muscles in the highly pronated foot. In the highly pronated foot, there is significantly greater EMG activity in the abductor hallucis and the flexor hallucis brevis muscles. This study by Mann and Inman did not observe the adductor hallucis as did Shimazaki. (From Mann and Inman,[102] with permission.)

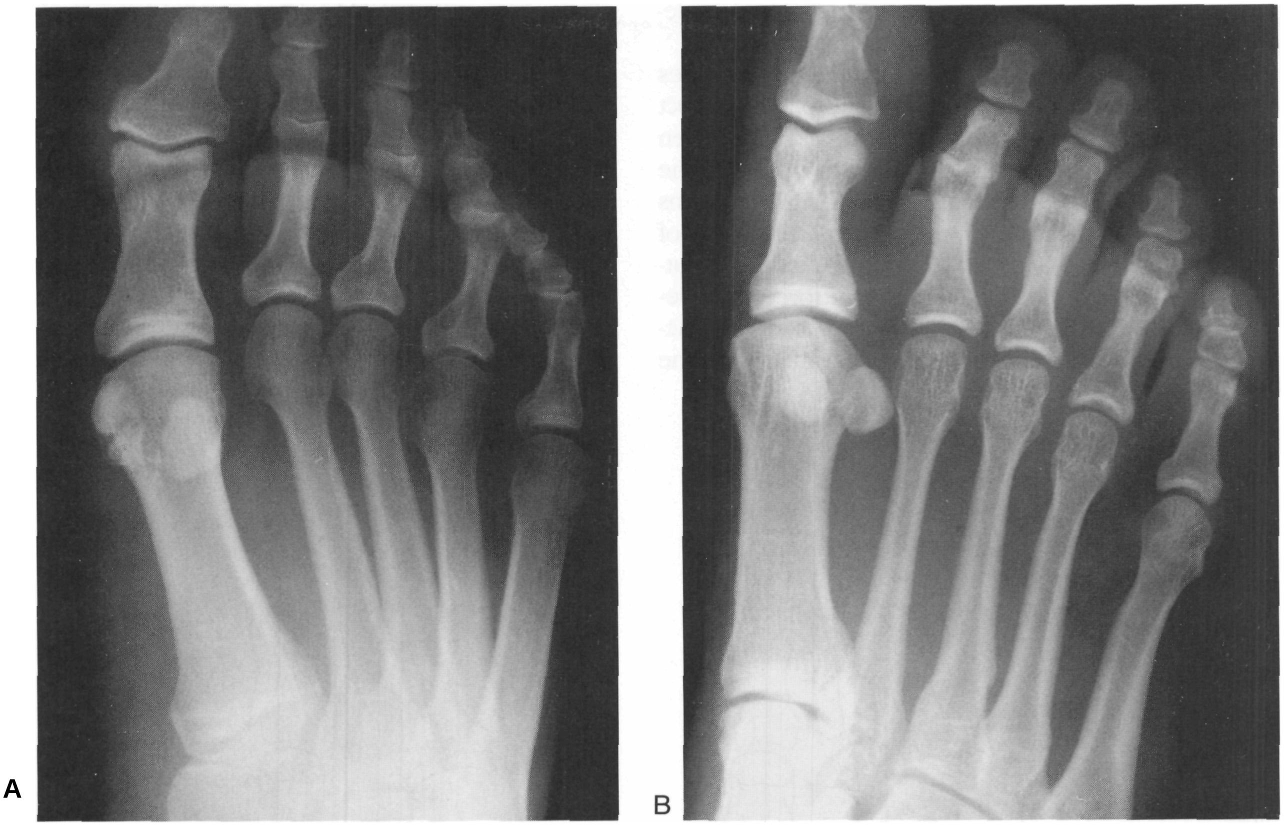


Fig. 3-13. (A) Radiograph of normal foot that is supinated. (B) Radiograph of the same foot when the foot is pronated. Note the appearance of "lateral displacement" of the sesamoids and the hallux, which is actually caused by the first metatarsal dorsiflexing and inverting.

has moved further away, such that if the adductor hallucis, the flexor hallucis brevis, and the abductor hallucis would all contract with equal force there would be a net lateral motion of the joint. In viewing the lateral sesamoid movement on the frontal plane, it is noted that the medial sesamoid has also moved in a plantar direction to lie under the crista of the first metatarsal head, while the lateral sesamoid has also moved in a dorsal direction, around the side of the head of the first metatarsal (Fig. 3-14). Erosions appear in the tibial sesamoid, and degeneration of the plantar metatarsal crista also begins. lida and Basmajuian[105] have demonstrated that once the hallux is in an abducted position, when the abductor and adductor hallucis muscles contract, there is a decreased force ex-

Fig. 3-14. As the hallux becomes displaced laterally, the tibial sesamoid encroaches and compresses the plantar crista of the first metatarsal head.

erted by both but the abductor hallucis force is decreased more than the adductor hallucis force.

As the medial sesamoid moves laterally, it impinges upon the intersesamoidal ridge on the plantar aspect of the first metatarsal head. Chondromalacia and then erosions first appear, followed by an erosion of the crista altogether.[106,107] In addition, new cartilage forms for the lateral sesamoid on the plantar lateral side of the first metatarsal head.[108] With the hallux in this laterally deviated position, compression forces are decreased in the center of the metatarsophalangeal articulation and increased around the periphery of the phalangeal articulation.[109] Thus, the medial rim of the phalanx increases its pressure into the metatarsal head as it goes through its dorsiflexion motion, creating articular cartilage disorganization, degeneration, and atrophy[10] and forming a groove into the medial side of the metatarsal head.[111] Once this groove has been formed, the articular cartilage medial to it begins a disuse atrophy and eventually disappears altogether. This gives the appearance of a hypertrophy of the medial head of the first metatarsal, but if the medial prominence of the first metatarsal head relative to the shaft of the bone is measured it will be found to be the

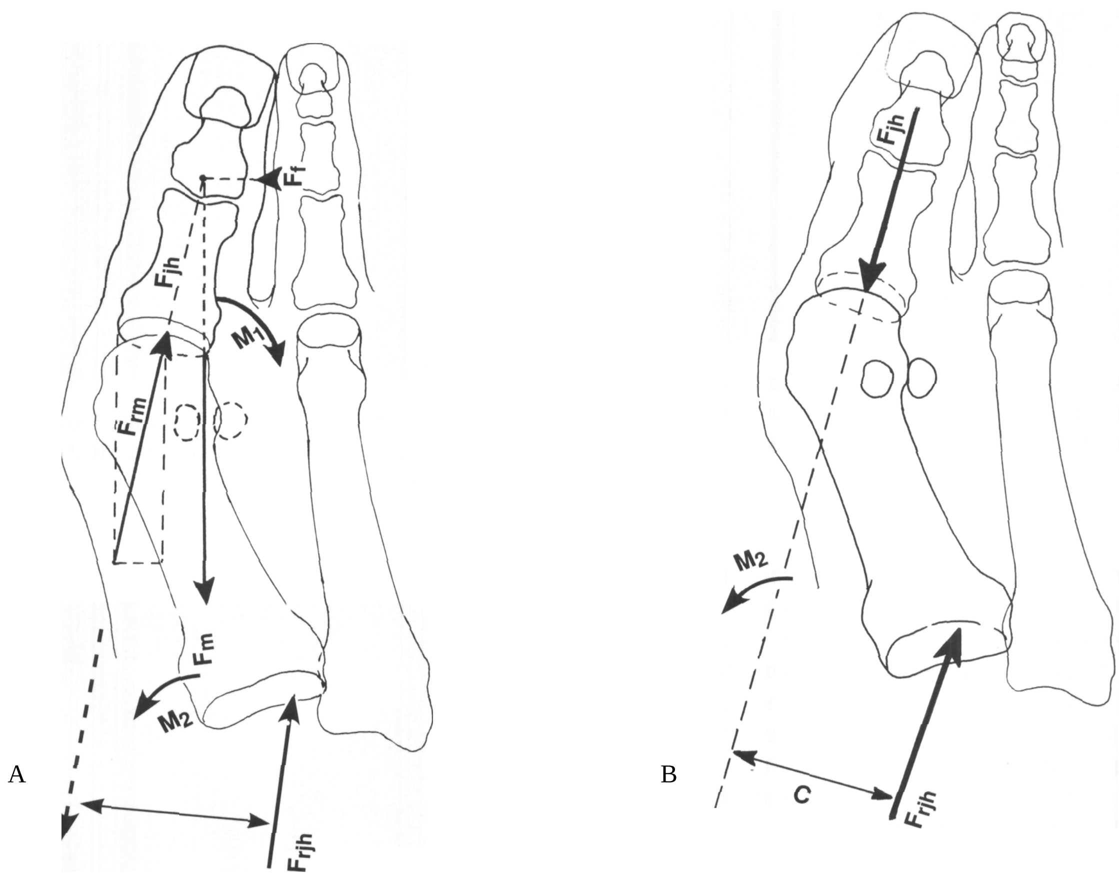


Fig. 3-15. (A) When the hallux is in an abducted position, the pull of the flexor hallucis longus (F_m) creates an abduction moment around the vertical axis of the first metatarsophalangeal joint (MO. It also produces a compressive force within the first metatarsophalangeal joint (F_{rm}) and a friction force against the ground (F_f). (B) The equal and opposite force of F_{rm} (labeled F_{jh}) and the compressive force in the first metatarsocuneiform joint (F_{rjh}) combine to create an adduction moment of the first metatarsal (M_2), which would increase the first intermetatarsal angle. (From Snijders et al.,[134] with permission.)

same size in both the normal and the hallux valgus foot. The medial eminence is thus the original medial epicondyle of the first metatarsal.[112]

The flexor hallucis longus proceeds forward, lying directly plantar to the intersesamoidal ligament. In a normal foot, the vertical axis of the metatarsophalangeal joint passes directly through the flexor hallucis longus tendon such that when the muscle contracts a straight compression is produced on the plantar aspect of the joint, causing the joint to move straight down (Fig. 3-15). In hallux valgus, however, with the sesamoids displaced laterally, the vertical axis lies medial to the tendon. There is therefore a lever arm between the flexor hallucis longus and the vertical axis, which means that when the flexor hallucis longus contracts, it places a torque to pull the hallux into an abducted position (Fig. 3-16).

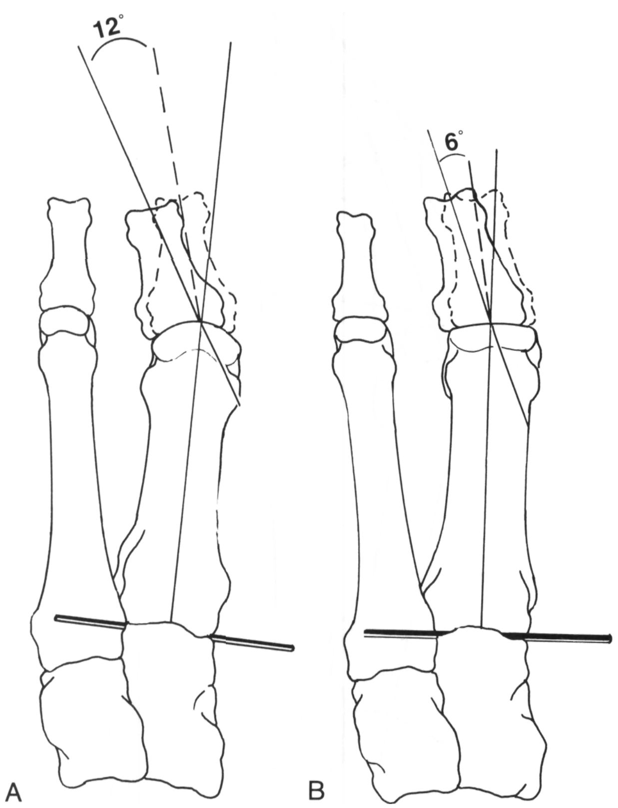


Fig. 3-16. A comparison of (A) a round first metatarsal head and (B) a flat first metatarsal head shows that the same linear displacement laterally of the base of the first proximal phalanx results in twice the angular displacement on the round head as that on the flat head. (From Mann and Coughlin,[166])

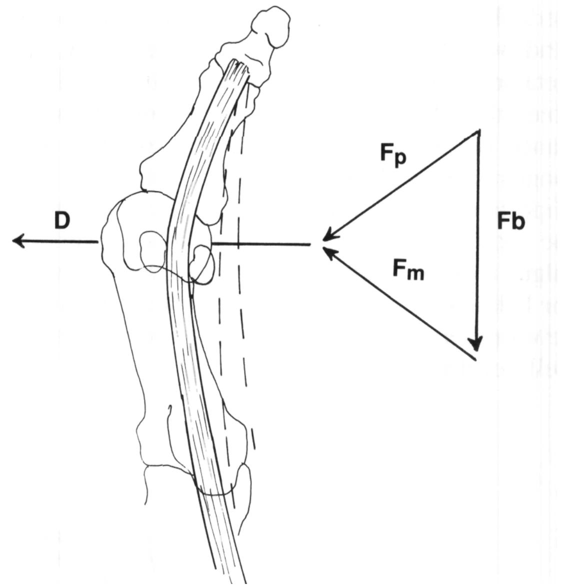


Fig. 3-17. The extensor hallucis longus does not actually bowstring the first metatarsophalangeal joint as was often drawn (dotted line), but is held in place by the extensor hood. However the pulley action around the first metatarsophalangeal joint does create a resultant buckling force (D —>) to push the first metatarsal medially. (From Rega and Green,[113])

Some individuals have implicated the extensor hallucis longus in the formation of hallux valgus, noting that it bowstrings laterally to the metatarsal head in patients showing the deformity thus when it contracts would create an abduction of the hallux. Rega and Green,[113] and also Schuberth et al.,[114] however, have shown that the extensor hallucis longus does not shift to any great extent laterally over the center of the head of the metatarsal, but instead remains anchored over the metatarsophalangeal joint by the extensor sling mechanism, functioning very much like a pulley (Fig. 3-17). Brahm[115] has shown that the more rounded the head of the first metatarsal in the transverse plane, the greater is the likelihood of the hallux buckling lateralward. If the toe becomes very much abducted, then the extensor hallucis longus would pull the base of the hallux in a proximal medial direction putting a medially directed push against the first metatarsal head, which would increase the distance of the first metatarsal away from the second.[116] It should also be noted that all the plantar muscles contract during the stance phase of gait, whereas the extensor hallucis longus is basically a swing-phase muscle. If it was an important direct contributor of hallux valgus, the great toe would become more dorsiflexed, without the valgus rotation, with increasing deformity. The extensor hallucis longus is more likely to contribute to the development only after the hallux abductus is already well developed.

THE DEVELOPMENT OF METATARSUS PRIMUS ADDUCTUS

Truslow[117] is given credit for coining the term *metatarsus primus varus* although others had recognized the deformity and recommended treating it before him. Many of the treatment failures have been ascribed to failure to fully treat the first metatarsal deformity.[118] In reality, the deformity is mainly a transverse plane deformity and therefore should properly be called metatarsus primus adductus or metatarsus

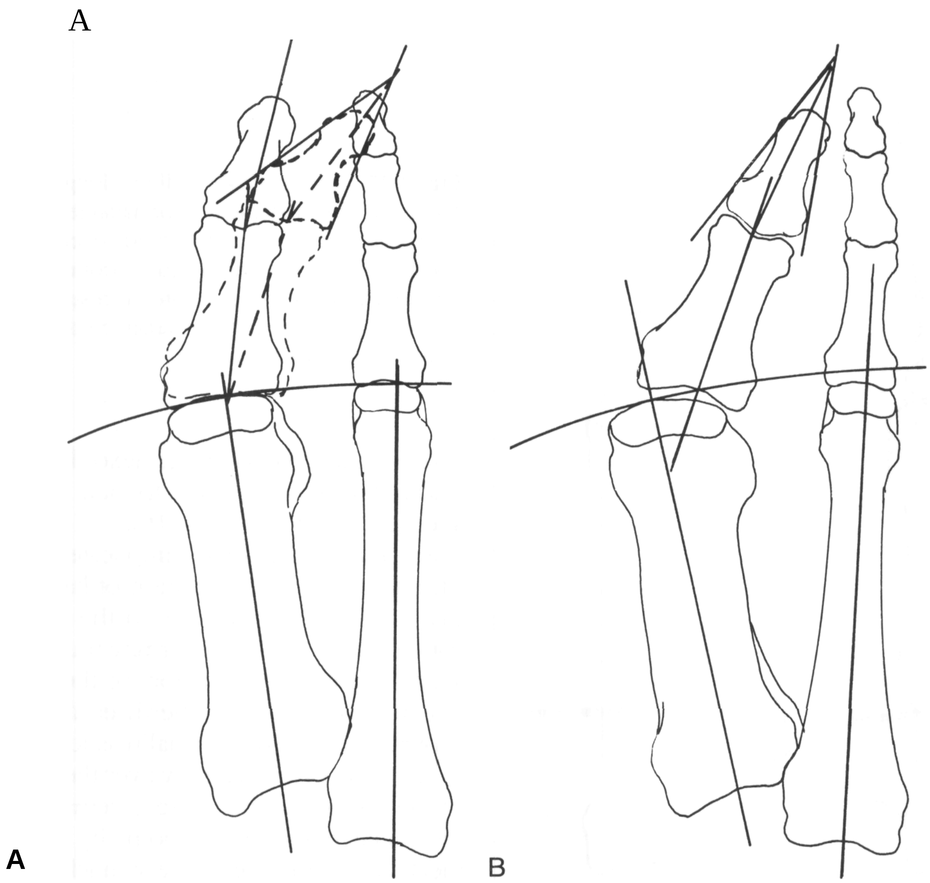


Fig. 3-18. The relationship between hallux abductus interphalangeus angle and the ability of the second digit to stop the development of hallux valgus. (A) The interphalangeal angle is high, which means that the metatarsophalangeal joint can abduct very little before the hallux makes contact with the second digit. (B) The interphalangeal angle is low, which means that the metatarsophalangeal joint can abduct much more before the hallux makes contact with the second digit. Thus, greater moments are present in Fig. B than in Fig. A, to adduct the first metatarsal, increasing the intermetatarsal angle. (From Duke et al.,[127])

primus adducto varus. It is recognized by an increased angle and distance between the first and second metatarsal heads (Fig. 3-18). Many individuals have found a correlation between the degree of hallux abductus and the first-second intermetatarsal angle, although it has not been a perfect linear correlation.[119] The exact degree of the distance or angle between the first and second metatarsal that demarcates normal from abnormal has been discussed numerous times. It has been usually proposed that a 5°-9° angle between the first and second metatarsals be considered to be the normal value.[120] However, it has also been proposed that if the angle between the first and fifth metatarsals is greater than 29° then an abnormal intermetatarsal angle may be less than a pathologic 10°.[121] Many have also observed that a general splaying of the entire forefoot often occurs, although the increased spread of the lesser metatarsals is quite small compared to that in the first intermetatarsal space. It is now well accepted that any treatment of bunions without the treatment of the concomitant metatarsus primus adducto varus will produce very little benefit to the patient, because the hallux valgus deformity will usually reoccur in a short period of time. There have been many explanations given for the development of the increased space between the first and second metartarsals, and they all probably contribute to this important aspect of the deformity.

It is now accepted that hallux valgus complex is a progressive disorder in which the hallux begins to deviate and then proceeds to subluxation.[122] It has been noted that there is a relationship between the degree of hallux abductus and the first intermetatarsal angle, in that as the degree of hallux abductus increases so does the degree of the first intermetatarsal angle. Girdlestone and Spooner[123] explained that so long as the proximal phalanx created compression directly proximal, that the first metatarsal would be stable, and that the increase in the first intermetatarsal angle would result from the first metatarsal escaping from the stabilizing effect of the proximal phalanx. Hardy and Clapham[124] noted in children with hallux valgus that the displacement of the great toe occurred usually before the age of 14 while the intermetatarsal angle did not show much increase until after the age of 15, thus arguing against the metatarus primus adductus being the primary deformity. Robbins[125] noted that the degree of intermetatarsal angle increase is very slow until the combined angle of the proximal phalanx abductus with the first metatarsal plus the distal phalanx abductus with the proximal phalanx reaches about 30° of abduction. After this, the slope of the relationship line between hallux abductus and first intermetatarsal angle increases approximately 10 fold, such that there are relatively larger increases in the degree of the first intermetatarsal angle for increases in the hallux abductus angle.[125] Viladot[126] noted that feet in which the great toe was shorter than the second showed fewer abnormalities than those in which the great toe was longer than the second. Duke et al.[127,128] showed that the greater the length of the first metatarsal, or the greater the abductus angle between the proximal and distal phalanges of the hallux, the greater the likelihood of bunions and the less the hallux abductus angle increase for the degree of intermetatarsal angle increase (Fig. 3-18). The demonstration by Hewitt[129] that hallux valgus and hammer toe of the second digit occurred eight times more frequently than either deformity separately reinforces the implication that the second toe acts as a buttress to prevent excessive lateral motion of the hallux. Thus the hallux may be fairly free to move laterally until it abuts against the second toe, and if the hallux is to move further laterally, either the second toe will have to move out of the way or the hallux must move on top of or under the second toe. Heden and Sorto[130] confirmed that the average patient with hallux valgus showed a mildly longer first metatarsal and also a longer proximal phalanx. Thus the greater the degree of interphalangeal joint abductus, or the longer the digit, the less the great toe will be able to adduct before it comes into contact with the second digit. Levick argued that as long as the second digit was fully stable, that the second digit would act as the origin for the first dorsal interosseous muscle, which would be the major force that would prevent the first metatarsal from moving medially away from the second metatarsal.[131] Stein[132] also attributed stability of the first metatarsal on the transverse plane to muscle action, but argued that it was the abductor hallucis that compressed the metatarsophalangeal joint on the medial side, which prevented the first metatarsal from moving medialward.

It has been noted that with the lateral movement of the hallux the net muscular pull by all the plantar muscles produces a lateral torque around the vertical metatarsophalangeal joint axis. After the hallux has contacted the second digit, which approximates the critical angle that Robbins discussed, the resistance of the second digit to being abducted increases the medial force against the first metatarsal head with muscular contraction. When the hallux is pulled laterally and is compressed against the first metatarsal head, there is also a direct medial force effected against the first metatarsal head, which would push the first metatarsal away from the second metatarsal. Bojsen-Moller[133] calculated that the medial force against the first metatarsal head was equal to the posterior shear force that the hallux placed against the ground times the tangent of the hallux abductus angle. Snijders et al.[134] developed a more complete model, showing that, as the hallux abductus angle increases, there is an exponential increase in the abducting moment around the metatarsophalangeal joint and the adducting moment at the metatarsocuneiform joint when the flexor muscles contract. Thus the marked increased in the intermetatarsal angle is observed with increasing degrees of hallux abductus.

When one first starts looking at radiographs of feet with hallux valgus, the intermetatarsal angle is reminiscent of the skeletal shape of the primates, with the marked first intermetatarsal angle. It has been hypothesized that the increased first intermetatarsal angle is an atavistic trait.[135] Many have stated that those with metatarsus primus adducto varus have a first metatarsocuneiform joint surface that is deviated medially from being perpendicular to the second metatarsal (Fig. 3-19), and that correction of the bunion involves correction of this angle by either joint fusion or first cuneiform osteotomy.[136] Although this deviation appears in many cases of increased intermetatarsal angle, there have been no studies on the potential association of the increase deviation with the first intermetatarsal angle. It may be that if the joint surface angle is increased medially, then the first metatarsal is more likely to move medially,[137,138] or it may be that this increase in the angle is an optical illusion caused by other malalignment of the foot. Elftman and Manter noted that the relationship between the forefoot and the rearfood in man resembled that of the foot in the chimp when the midtarsal joint was supinated,[139] or the corollary to this could be that when the forefoot is pronated against the rearfoot in humans that it begins to resemble the shape of the chimpanzee foot.

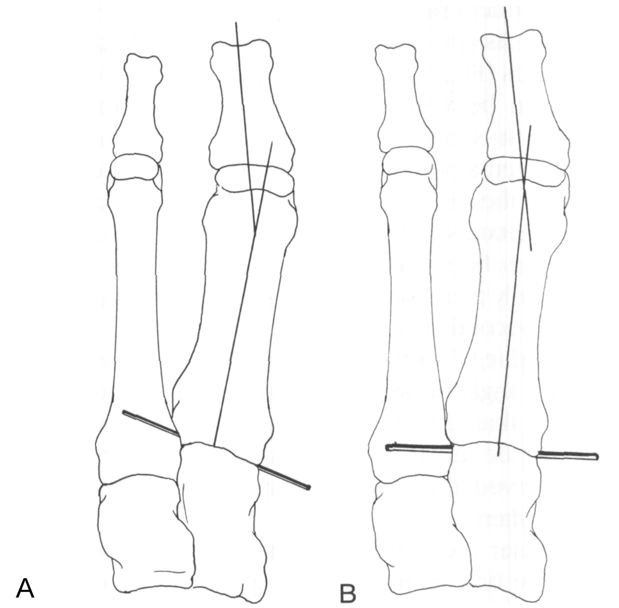


Fig. 3-19. (A & B) It has been hypothesized that an atavistic metatarsocuneiform joint that is oriented medially as in Fig. A is more likely to develop metatarsus primus adductus than a metatarsocuneiform joint that is oriented to face more anteriorly as in Fig. B. (From Mann and Coughlin.[166])

As noted previously, Kelso et al. confirmed the Hicks model of the first metatarsal motion as being a dorsiflexion—inversion or a plantar flexion-eversion motion relative to the second metatarsal. Jones[140] and then Manter[141] demonstrated that normally the first metatarsal bears approximately twice the load of the other metatarsals. Although Mayo[142] and Nilsonne[143] have noted that a majority of hallux valgus cases show the first metatarsal longer than the second metatarsal, which would normally throw increased weight-bearing onto the first metatarsal head, Stokes et al.[144,145] and Hutton and Dhanendran[146] have shown, in patients with hallux valgus, a decrease in weight-bearing under the first metatarsal and a transfer of weight laterally under the lesser metatarsals. Wyss et al.[147] showed that there is normally a force of approximately 350 newtons between the sesamoids and the metatarsal head. This amount of force would normally prevent the medial sesamoid from being able to ride over the central crista, so the first metatarsal head must become unweighted for the medial sesamoid to displace laterally.

Metatarsalgia is commonly a reported symptom in the hallux valgus complex, and it may be explained by decreased weight-bearing of the first metatarsal. Morton[148] first referred to this condition as hypermobility of the first metatarsal. Decreased weight-bearing of the first metatarsal could be seen in a patient who walks on the lateral side of the foot, or it may be seen if the first metatarsal moves in a dorsal direction relative to the second. It can also been seen if there is lack of muscular activity that would stabilize it against the ground. Because almost all patients with hallux valgus show the sesamoids everted laterally under the first metatarsal, it has been argued because of the strong ligamentous support between the sesamoids and the second ray that it is not the sesamoids that have everted against the first metatarsal but instead the first metatarsal has inverted relative to the sesamoids. It should be noted that, for the medial sesamoid to move laterally under the plantar crista, some loss of compression must occur between the sesamoid and the metatarsal head. Thus the first metatarsal head would have to decrease its weight-bearing load, then invert to produce the change in the sesamoid position. Galland and Jordan[149] first supported this view that the increase in the intermetatarsal angle was caused by the first metatarsal dorsiflexing and adducting, which gave the impression that the transverse metatarsal arch had fallen.

The reason for decrease in the weight-bearing load and inversion of the first metatarsal has been hypothesized to result from two factors: an eversion of the midfoot and rearfoot, and a loss of plantar-flexing force by the peroneus longus. The relationship between the pronation of the rearfoot and the development of hallux valgus has long been noted; seldom has hallux valgus been observed to develop with a high arch or supinated foot.[150] Lundberg and Sulja[151] argued that the increased length of the first metatarsal seen in patients with hallux valgus is caused by the dorsiflexion of the first metatarsal that occurs when the foot pronates. Inman[152] demonstrated that when a normal foot is radiographed in a pronated position, the sesamoids are seen to move laterally from being centered under the first metatarsal. Greenberg[153] showed a positive correlation between the combined transverse plane pronation in the subtalar and midtarsal joints and the degree of hallux valgus, Ross[154] showed a positive correlation between the fall of the arch in weight-bearing and the degree of hallux valgus, and Stevenson[155] has shown more certainly a positive correlation between the eversion of the rearfoot and the development of hallux valgus. The possible relationship between pronation of the rearfoot and the development of hallux valgus has been explained with many types of models.

The first explanation is that when the rearfoot everts, the foot becomes more abducted to the line of progression. As the foot becomes abducted to the line of progression, the toe will no longer tend to dorsiflex during propulsion in a line perpendicular to the articular surface of the metatarsal; instead, the foot will lift off, and move in a medial direction to the toe during propulsion. In other words the toe will dorsiflex and abduct to the metatarsal during propulsion (Fig. 3-20).

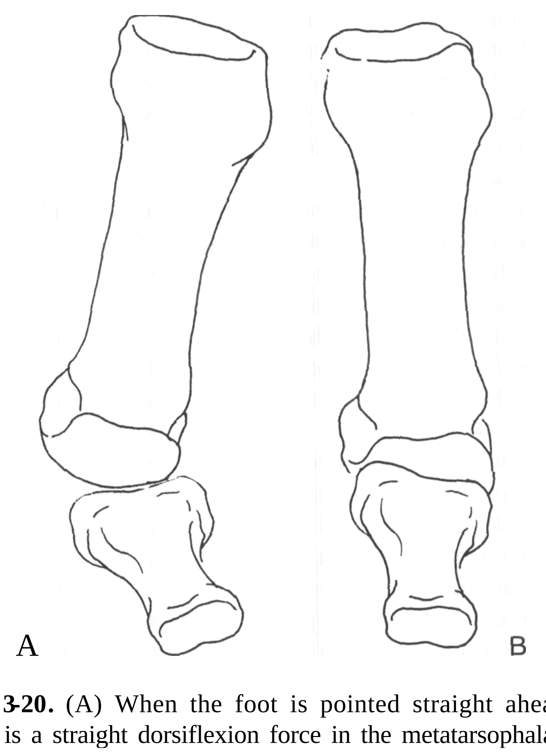


Fig. 3-20. (A) When the foot is pointed straight ahead, there is a straight dorsiflexion force in the metatarsophalangeal joint during propulsion. (B) If the foot is abducted, then the hallux will also abduct against the metatarsal head as it dorsiflexes during propulsion.

It is noted that when the rearfoot everts all the metatarsals evert to the surface, which would transfer the weight onto the medial three metatarsals. The natural inclination is for all the metatarsals to seek equal weight-bearing. This can be accomplished by two mechanisms: inversion of the midfoot at the midtarsal joint, or dorsiflexion of the medial metatarsals, starting at the first. If the first metatarsal remained in its neutral position, it would still be plantar to the second metatarsal, which is also everted. Thus the first metatarsal must dorsiflex above its neutral position to be at the same, level. This dorsiflexion would also be accompanied by an inversion motion relative to the second metatarsal. It is also noted that an eversion of the midfoot would also cause the first-ray axis to project in a more dorsal-distal direction, which would mean that there would be more relative adduction of the first metatarsal away from the second metatarsal as it dorsiflexed and inverted. It is noted that the second metatarsal has a much smaller range of motion than the first metatarsal; thus, although the first metatarsal may be able to seek a level at the same height as the second metatarsal, the second metatarsal is still below the level of the third and thus weight may be borne by the second metatarsal that the lateral forefoot may have borne previously (Fig. 3-21). Thus it is not uncommon for a callous to develop under the metatarsal head with hallux valgus.

The fact that the first metatarsal may dorsiflex and invert relative to the second metatarsal does not answer the question as to why the first metatarsal weight-bearing may be less than the weight-bearing under the second. Even though the first metatarsal may dorsiflex to the level of the second, the lateral three metatarsals are still off the ground, and thus the midtarsal joint would have to accept the function of placing these metatarsals onto the ground. Hicks proposed a midtarsal joint that allows almost pure frontal plane motion around a longitudinal axis that places the first two metatarsals medial to it and the other three lateral to it. Thus an upward pressure of the ground under the first two metatarsals would place an inversion force against the longitudinal axis of the midtarsal joint until force against the lateral three metatarsal heads is equalized. As the forefoot inverts around the longitudinal axis of the midtarsal joint to place the lateral three metatarsal heads onto the ground, the first metatarsal will tend to rise off the ground, decreasing its weight-bearing load. A common finding then is to have not only a callus under the second metatarsal but also one under the third metatarsal, meaning that equilibrium has been achieved around the longitudinal axis of the midtarsal joint but without achieving full weight-bearing across all the metatarsal heads. This phenomenon of callous buildup, which was commonly attributed to a collapse of the metatarsal arch, is now easily explained by the combined actions of the subtalar, midtarsal, and first-ray axes when the foot pronates.

The determination of whether the longitudinal axis of the midtarsal joint completely accounts for the pronated rearfoot, or whether the first ray dorsiflexes-inverts, and to what degree each occurs, must be determined by a study of the location of the axis of each. When force is placed upward against the first metatarsal, a dorsiflexion force is placed against the first ray and also a supination force is placed against the longitudinal axis of the midtarsal joint. The joint that moves first then is dependent on which joint has the stronger torque being placed upon it. Because torque is equal to the force (both of which are equal) multiplied by the lever arm multiplied by the sine of the angle between the force and the axis of motion, whichever joint has the longer lever arm and the axis that is closer to being parallel with the ground will move first to the end of its range of motion. Thus if the foot moves first around the longitudinal axis of midtarsal joint, and if there is adequate motion in the joint for it to fully compensate for the rearfoot pronation, then there would be no need for the first ray to dorsiflex and invert relative to the second. Thus a pronated rearfoot may never show any signs of a hallux abducto valgus or metatarsus primus adductus deformity. Unfortunately, no clinical methods have been proposed for determining the location of the midtarsal joint or first-ray axes nor of quantifying the degree of motion around the midtarsal joint axis. Once these methods have been developed then a multifactorial analysis may indeed prove these hypotheses.

The question may be asked as to why the first metatarsal does not plantar flex as the longitudinal axis of the midtarsal joint supinates. The answer may be that it passively does because gravity pulls the first ray downward; however, it still fails to develop a force underneath. The most common explanation for this phenomenon has been that force underneath the first metatarsal head is generated by the peroneus longus

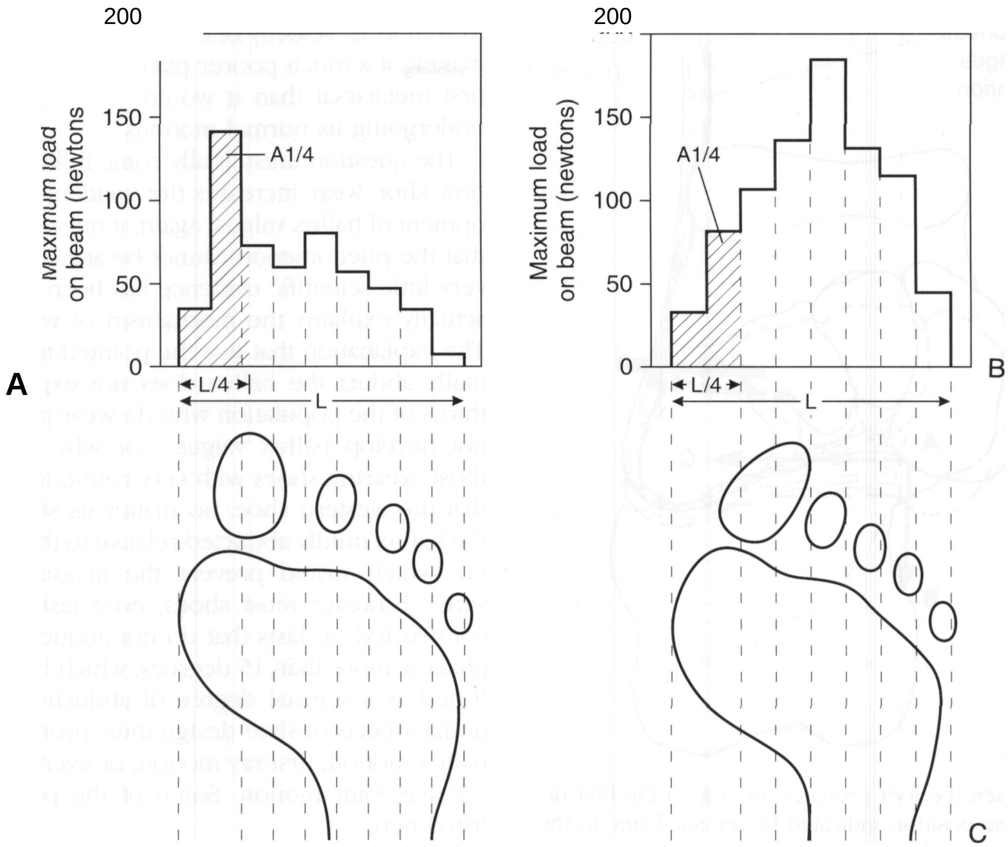


Fig. 3-21. Peak loads recorded across the forefoot in a typical normal and a typical hallux valgus foot. (A) In the normal foot the first metatarsal bears approximately twice the peak load as any of the other metatarsals. (B) In the foot with hallux valgus, there is a loss of weight-bearing load by the first metatarsal and transference of peak loads to the second and third metatarsals. This produces a callus formation under the second and third metatarsal heads because of the increased weight transference. (C) A Harris Beath Mat records clinically the transference of weight from the first metatarsal head to the lesser metatarsals. This transference of weight was described by Dudley Morton as hypermobility of the first ray. (Figs. A and B from Stokes et al.,[145] and Fig. C from Harris and Beath,[167])

as it pulls the first metatarsal-first cuneiform in a plantar-lateral eversion direction (Fig. 3-22). Hicks[156] noted that the peroneus longus has a strong arch-raising function because of its strong plantarflexion force on the first metatarsal. The amount of plantar pulling is directly proportional to the height change between the lateral side of the cuboid and the base of the first metatarsal, and also on the stability of the cuboid on the calcaneus. The greater the height change between the medial and lateral sides of the foot, the greater the proportion of the pull of the peroneus longus that can be converted into pulling the first metatarsal down against the ground. As the rearfoot everts, which causes the height of the arch to drop, the less proportion of the peroneus longus pull that can be converted into a plantar force of the first metatarsal against the ground. It should also be noted that the peroneus longus also pulls the cuboid laterally and in an eversion manner, and that to exert all its force into the first metatarsal the cuboid must be stabilized firmly against the calcaneus. This is usually accomplished by the midtarsal joint passively reaching the end of its pronation motion around the longitudinal axis before heel lift. However in the pronated foot, the peroneus

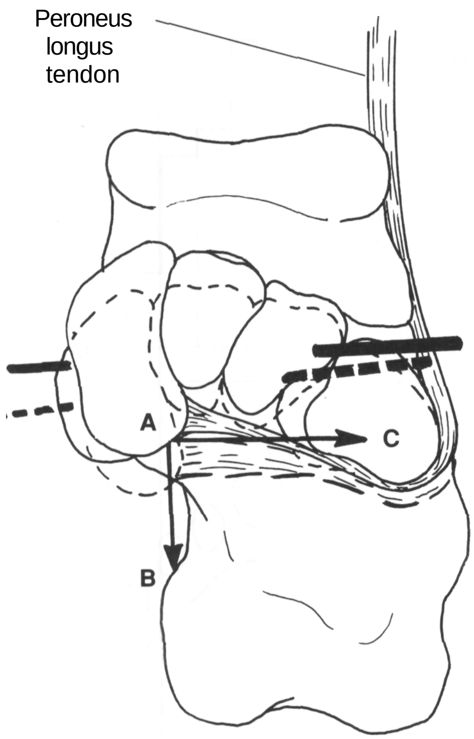


Fig. 3-22. When the foot pronates the axis of the first ray moves from the position indicated by the solid line to the position indicated by the dotted line. The insertion of the peroneus longus to the plantar first metatarsal also moves downward, which decreases the plantar component of its force vector.

longus is also attempting to actively evert the cuboid, which would then force the first metatarsal into a more dorsiflexed-inverted position. Thus normal stabilization of the first ray against the ground by the peroneus longus is aided by the active inversion of the rearfoot, which is passively everting the cuboid against the calcaneus. The final consideration of the action of the peroneus longus has to do with its length. In the normal foot, the supination of the rearfoot increases the length of the peroneus longus. This lengthening of the muscle increases its plantar pull and the velocity with which it can contract. In the pronated foot, with the calcaneus everted and the midtarsal joint more abducted to the rearfoot than in the neutral foot, the peroneus longus is in a shortened position. The force with which it can contract in this shortened position, as well as its velocity of contraction, is thus decreased making it a much poorer plantar flexor-evertor of the first metatarsal than it would be if the rearfoot was undergoing its normal motions.

The question must finally come full turn again as to how shoe wear increases the incidence of the development of hallux valgus. Again, it must be emphasized that the phenomenon cannot be argued even though very little scientific evidence has been presented that actually explains the mechanism of why it happens. The explanation that it is the pointed toes that abnormally abduct the hallux does not explain why two-thirds of the population who do wear pointed toes do not develop hallux valgus, nor why it develops in those wearing shoes with very round toes. The fact is that the western shoe, no matter its style, does hold the hallux mildly abducted relative to the first metatarsal, which would prevent the incidence of hallux varus; however most shoes, even fashion ones, are constructed on lasts that do not abduct the proximal phalanx more than 15 degrees, which has been established as a normal degree of abduction. Thus additional aspects of shoe design must promote abnormal hallux motion, first-ray motion, or even midtarsal and subtalar joint motion. Some of the possibilities are listed here.

Henderson[157] stated that the failure in the strength of the arch is the cause of most of the ills of the human foot. He noted that foot ills, including weak painful feet, are practically unknown in aboriginal feet. He hypothesized that shoes inhibit the development of the important arch-supporting muscles within the foot.

Ceeney[158] noted that shoes must not only fit the foot by size, but that the shape of the shoe must also fit the foot. Many shoes that are well fit by size requirements still do not match the shape of the foot, and thus will not make the foot comfortable. Root et al.[159] stated that hallux abductus only occurred in feet with an adducted forefoot type. Because most shoes seem to hold the long axis of the digits parallel with the long axis of the rearfoot,[160] they hypothesized that the more the forefoot is adducted to the rearfoot, the more the shoewear will hold the hallux abducted to the first metatarsal, which would tend to move the sesamoids into a more lateral position to initiate the hallux abductus (Fig. 3-23). Lindsay[161] also argued that most

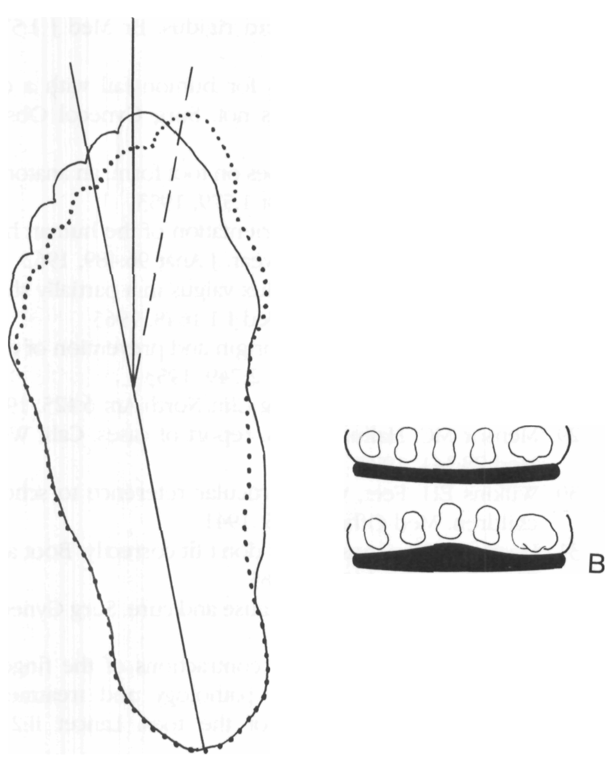


Fig. 3-23. (A) An adducted forefoot type (solid line) that is placed in a straight last shoe will pronate in the rearfoot to place the forefoot in a more rectus position (dotted line). (B) It is also noted that most shoes are built on the inside with the area under the central metatarsal heads lower than the surface under the first metatarsal head. It has been hypothesized that this may also contribute to abnormal dorsiflexion of the first metatarsal inside the shoe. (From Lindsay,[161])

shoes are not built with adequate forefoot adductus. In relationship to this is the fact that few, if any, persons when they buy shoes try to find a shoe built on a last with the same degree of forefoot adductus that exists in their foot when the subtalar joint is in its neutral position. Emslie[162] pointed out that if a foot with an adducted forefoot morphology is placed into a shoe that has less forefoot adductus than the foot, then the subtalar joint will be forced to pronate to allow the forefoot to abduct to the rearfoot to fit into the shoe; the midtarasal joint, by being unable to supinate, will prevent adequate propulsion. Thus many people with a forefoot adductus morphology may be fitting their feet into shoes with a last that is too straight and which is inducing hallux valgus because of these the pronation mechanisms.

Lindsay also argued that shoes are built with the bottom of the sole convex, which would cause the third metatarsal to seek the lowest level. This would cause the first and fifth metatarsals to tend to dorsiflex above the level of the other metatarsals, which may also initiate a relative lateral movement of the hallux, especially in a new shoe. While the frontal plane convexity of the sole is necessary for manufacturing processes, some shoe companies have responded by placing a metatarsal "cookie" just behind the central metatarsal heads to allow the first and fifth metatarsals to plantar-flex to or slightly below the level of the central three.

Early writers often blamed a high heel for the cause of bunions, describing the shoe as being too short, too long, too narrow, etc. Raising the heel height does increase the weight that is pushed forward and cause the metatarsophalangeal joints to function in a more dorsiflexed position and the plantar fat pad to be pulled forward. It might be possible that the dorsiflexed position of the hallux could induce a plantar movement of the first metatarsal and cause the foot to function as if the patient had an everted forefoot condition. Such everted forefoot conditions do induce a pronatory motion during propulsion in an attempt to move body weight onto the opposite foot. Phillips et al.[163] hypothesized that it was not a high-heeled shoe in and of itself that induced hallux valgus, but that possibly most high heels have a very small heel area and that pronation of the foot occurs just before propulsion, which was concluded to occur because the small heel surface prevented the foot from supinating. They demonstrated that if the heel of the shoe was moved medially approximately 3-4 mm that the pronation of the foot decreased before it entered propulsion.

There may be other factors in the shoe that could also cause the foot to pronate more than it would if the patient did not wear shoes. This question has not been satisfactorily answered by any researcher, nor do shoe companies produce data on new shoes that are introduced to show that the shoes increase or decrease the ability of the foot to function close to the ideal.

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