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The
FOOT

Review article

Biomechanics: a review of foot function in gait

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The way in which humans walk has been investigated by professionals from a variety of disciplines. The walking cycle is a coordinated series of movements occurring through the body, and in particular the lower limb. Many events happen simultaneously which makes description of the cycle difficult.[1] In essence, human locomotion is the translation of the body from one point to another by bipedal gait[2] — a form of locomotion evolved through our earliest ancestors which has been in use for more than a million years.[3] The whole of the musculoskeletal locomotor system has been adapted to an upright body position and bipedal gait, and the mechanisms of the foot have evolved and developed for the dual purpose of support and propulsion — its structure therefore is an expression of its function. The dynamically functioning foot is required to be, firstly, an adaptable structure of sufficient flexibility to accommodate variations in terrain and, secondly, to be a rigid lever which is able to transmit effectively the propulsive forces which are applied to it.

Standard references and anatomy texts offer little insight into how joints function together in gait and this has led to some difficulty in the understanding of the precise mechanisms of foot function, as the bones which carry the articular surfaces enclosed by a joint capsule do not necessarily act as a unified structural mechanism. A further difficulty in obtaining a clear understanding of foot function stems from the variations in the use of terminology.[4] When considering the functioning of the foot it is necessary to identify and distinguish movement about joint axes which may occur in one, two or all three body planes.

In gait, the functioning of the lower limb is a complex closed kinetic chain, but the significant mechanisms of foot function and normal biomechanical activity can be explained by concentrating on the three major contributing articulations, i.e. the ankle, and the subtalar and midtarsal joints.[5]

The ankle can be considered as a simple hinge with a frontal plane axis which passes from the higher medial malleolus to the lower lateral malleolus. The normal range of motion is 20° of dorsiflexion and up to 50° of plantarflexion (i.e. in the sagittal plane) from its neutral position when the foot is at 90° to the leg.[4] The degree of dorsiflexion sufficient for normal function varies between individuals[6] but 10° of dorsiflexion and 20° of plantarflexion are considered to be the minimum values.[7] The dorsiflexion allows the tibia to pass anteriorly over the joint, and if this motion is not available due to osseous limitation or tight musculature, some form of compensation will occur elsewhere in the limb leading to a pathomechanical problem.[5]

As a functional unit the subtalar joint (STJ) comprises the articulations between the talus and the calcaneus. The joint axis passes from plantar posterior and lateral to dorsal anterior and medial, it allows movement at right angles to the axis in all three body planes (i.e. pronation and supination).[8] It functions as a torque converter and its mechanism contributes to shock absorption in the limb.[1,5] The normal movement range is 30° of motion of the posterior aspect of the calcaneus in the frontal plane around the joint's neutral position where it is neither pronated nor supinated.[8,9] In general terms the neutral position is that from which there is twice as much supination as there is pronation,[10] however, it has been shown that there is wide variation of the neutral position among individuals[11] and the formula of 2/3: 1/3 supination: pronation may not be accurate in all cases. In addition, variations in the angulation of the joint axis with the transverse plane (which may show a normal distribution) will have an effect on the motion available in the frontal plane, e.g. the 'lower' the axis the more frontal plane motion (inversion and eversion) will be available, and with a 'higher' or more vertical axis, the opposite will be the case. However, the STJ neutral position, that of maximum congruity of the articular surfaces, provides a basis for foot stability and it is the position in which clinical assessment is made of the forefoot to rearfoot structural relationship, the first ray and of ankle dorsiflexion.

The functional unit of the midtarsal joint (MTJ) consists of the talonavicular and calcaneocuboid articulations. The unit has two axes of motion,[7,10,12,15,16] both of which are pronatory and supinatory, but the angulation of the axes and the motion about them are very different. The longitudinal axis allows mainly frontal plane motion, i.e. inversion and eversion, whilst the oblique axis allows mainly sagittal and transverse plane motion, respectively dorsiflexion/plantarflexion and adduction/abduction. The joint allows the forefoot to move relative to the rearfoot.

The biomechanical actions of these axes during gait are complex — motion about one axis can be independent of motion about the other, and as there are osseous components common to both the MTJ and the STJ, motion at the STJ has significant effects on the function of the MTJ. Firstly, STJ supination tilts the MTJ oblique axis so that it becomes more vertical and a greater proportion of movement occurs in the transverse plane (adduction/abduction). Conversely STJ pronation makes the MTJ oblique axis more horizontal which has the effect of reducing the amount of transverse plane motion and increasing the amount of sagittal plane motion (dorsiflexion/plantarflexion). Secondly, STJ motion changes the orientation of the axes of the MTJ articular facets (Fig. 1). As the STJ is prontated the calcaneocuboid axis becomes parallel to the talonavicular axis allowing the foot to become flexible. As the STJ moves from a pronated position through neutral to a supinated position, the facet axes become increasingly divergent and the bones lock together restricting motion at the joint and converting the foot into a rigid lever.[5,8,13,14] In addition, STJ pronation increases the MTJ range of motion and STJ supination decreases it and similar effects occur with the first and fifth rays.[7,15,16]

The action of the STJ therefore is important to the normal weight transmission through the foot, and it provides the mechanism which allows the foot to perform as a flexible adaptive structure, and then in turn be transformed into a rigid lever. Motion at the STJ occurs around its neutral position — a pronated joint providing for flexibility, neutral and supinated positions provide increasing efficiency in propulsion. In normal gait in a normal limb and foot the STJ undergoes a cycle of pronation and supination (Fig. 2).

An assessment of abnormal structure and function requires a comparison with normal criteria and the following biophysical relationships have been established as the normal structure of the foot and leg during midstance.[8,15,17] This orientation of the skeletal locomotor components ensures effective transmission of forces for the lowest energy cost and it is this physical alignment which is utilized when assessing the non-weightbearing limb:

1. With the knee extended, the patella lies on the frontal plane.
2. The bisection of the distal 1/3 of the tibia is continuous with or parallel to the bisection of the posterior surface of the calcaneus, with the foot at 90° to the leg.
3. The bisection of the posterior surface of the calcaneus is vertical to the supporting plane.
4. The subtalar joint is in its neutral position.
5. The midtarsal joint is fully pronated.
6. The plantar forefoot plane is parallel to the plantar rearfoot plane, and the bisection of the calcaneus (3) is perpendicular to the plantar plane of the foot.
7. When weightbearing, the metatarsal heads lie in the same plane touching the supporting surface.

The walking cycle consists of stance and swing leg phases and a complete walking cycle is considered to extend from heel strike of one leg to the next heel strike of the same leg, the relative duration of each phase depends on the cadence or speed of the walk.[3] The significant aspects of foot function take place during the stance phase and this has been analysed and described in many ways.[18–21] However, division

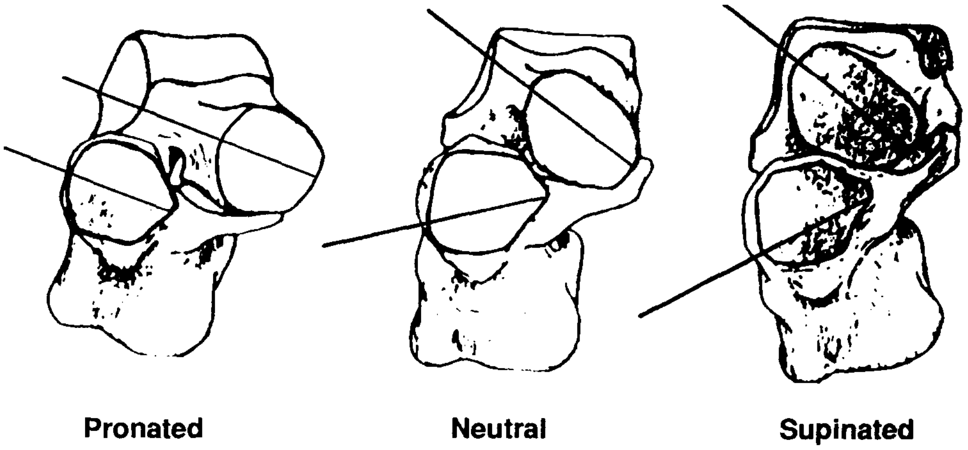

Fig. 1—Midtarsal joint locking (after Sgarlato).

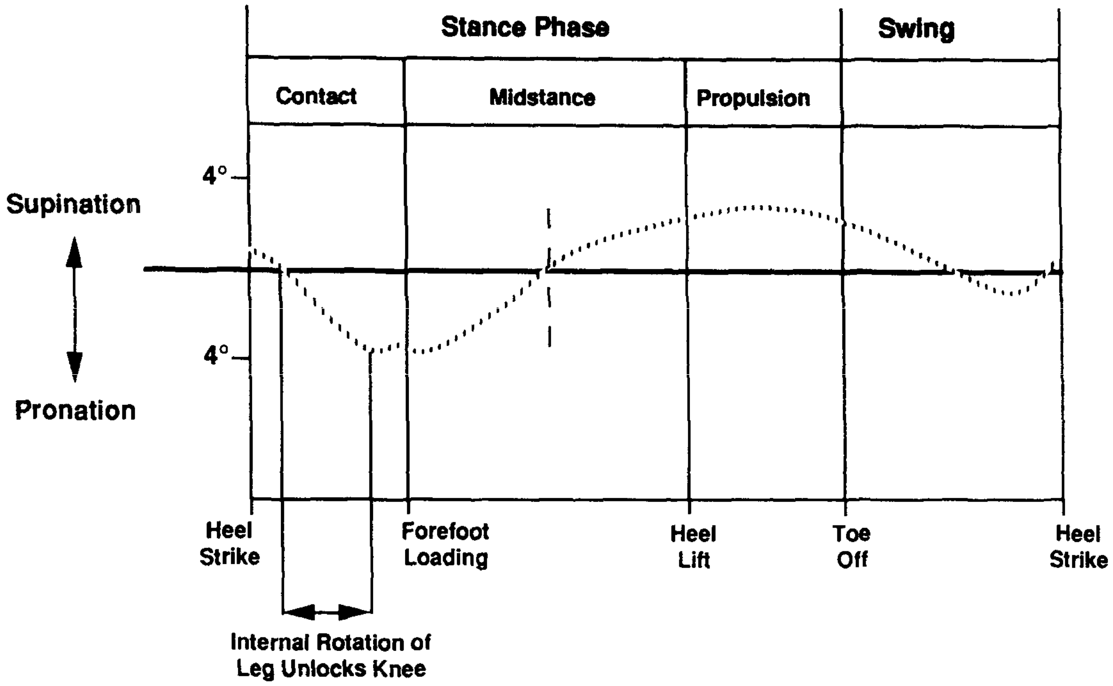

Fig. 2—Normal subtalar joint motion in gait.

of the weightbearing stance phase into three parts — contact midstance and propulsive periods facilitates clinical observation of motion and position.[7]

1. The contact period is the time between heel strike (HS) and forefoot loading (FFL). At HS the foot is slightly supinated and ground reaction force on the lateral side of the heel pronates the STJ until the heel is upright, a further 4.0° approx. of pronation is caused by internal leg rotation, and the metatarsus becomes fully loaded at the end of the contact period. The pronation provides for skeletal mobility to accommodate uneven terrain, variations in postural positions of the leg, and contributes to shock absorption. Pronation and internal leg rotation is stopped at the end of the contact period by the supinating force of tibalis posterior and other calf muscles.[7,22]
2. Midstance begins at the end of the contact period (at FFL) and ends at heel lift (HL). The foot is converted from a mobile adaptor to a rigid lever by STJ supination. The joint moves out of its most pronated position at the end of the contact period and into a supinated position prior to heel lift. The leg externally rotates throughout midstance and the STJ neutral position is reached at or soon after 50% of the midstance period.
3. During the propulsive phase from heel lift to toe off (TO) STJ supination and external leg rotation continue thus increasing the mechanical efficiency of the foot. Body weight shifts from the lateral side of the forefoot to the medial side and to the contralateral foot as it makes ground contact.[7,10]

It can be appreciated therefore that the action of the STJ and its role in the MJT locking mechanism is a vital part of normal foot functioning. Inversion of the rearfoot as body weight passes forwards directs ground reaction force laterally which exerts a pronatory force on the MTJ ensuring that the joint is locked. As described above, the MTJ becomes locked from the time the STJ reaches its neutral position, a point when the plantar plane of the forefoot is parallel to the plantar plane of the rearfoot. No further relative eversion of the forefoot is available so the whole of the foot inverts with the continued STJ supination. This allows the first ray to plantarflex (and evert slightly) — in order that the sesamoids can maintain ground contact as the heel rises — so that the first metatarsal head can form a firm base against which the hallux can be stabilized so that it can receive the loads which are transmitted during the propulsive period. Should the locking process of the MTJ be ineffective, the first ray function will also be compromised and forefoot deformities such as hallux rigidus and hallux abductovalgus will develop.[4,7]

If there are deviations from the ideal segmental relationships listed above the normal pattern of interdependent joint movements could be disturbed. When structural deformities exist in the foot it is the STJ which is most likely to compensate,[9] however, deformities usually exist in a single plane, but the compensatory motion at the STJ occurs in all three planes and is usually in the direction of pronation.[7,9,10] If this is the case, the MTJ locking mechanism, its role in the structural rigidity of the foot and therefore the foot's ability to withstand the propulsive forces applied to it, may be compromised.

Should pronation at the STJ occur at a time when the foot should be supinated, it will be functionally unstable (hypermobile). If conversely, the foot is supinated when it should be pronated, due to limited joint mobility or structural abnormality, flexibility and shock absorption will be compromised. Abnormal biomechanics of the foot can be caused by the many deviations from the ideal structural relationships, and four major abnormalities are commonly recognized (as described with the STJ in its neutral position) — rearfoot varus, forefoot varus, forefoot valgus (either as a total forefoot valgus or as a plantarflexed first ray) and an equinus deformity (less than 10° of ankle dorsiflexion).[5,8–10,17,23]

Any abnormal function in a foot could result in the ineffective transmission of forces, increased energy requirements, increased contact times, changed loading patterns and concentrations of ground reaction forces with a resultant overloading of plantar tissues and the subsequent formation of hyperkeratotic lesions such as corns and callosities. The location and distribution pattern of such overloading, and the development of forefoot deformity will depend on the pathomechanical mechanisms which result from the particular type and/or combination of structural abnormalities. Propulsive and ground reaction forces are of a magnitude to be potentially damaging, and disordered function could increase the risk factors caused by metabolic or systemic derangement.

References

1. Mann R A. Biomechanics of the foot. In: Gould J S Ed. The foot book. Baltimore: Williams and Wilkins, 1988: pp 48–63.
2. Saunders J B, Inman V T, Eberhart H D. The major determinants of normal and pathological gait. J Bone Joint Surg 1953; 35A: 543–558.
3. Napier J. The antiquity of human walking. Sci Am 1967; 7: 216: 56–66.
4. Foulston J. Biomechanical analysis of foot structure and function. Ballieres Clin Rheumatol 1987; 1: 2: 241–260.
5. McPoil T G, Brocato R S. The foot and ankle: biomechanical evaluation and treatment. In: Gould J A, Davies G J Eds. Orthopaedic and sports physical therapy, Vol II. St Louis: Mosby, 1985: pp 313–341.
6. Tiberio D. Evaluation of functional ankle dorsiflexion using subtalar joint neutral position. Phys Ther 1987; 67: 6: 955–957.
7. Root M J, Orien W P, Weed J H. Clinical biomechanics, Vol II. Normal and abnormal function of the foot. Los Angeles: Clinical Biomechanics Corporation, 1977: pp 36–43, 127–149, 252–284, 295–308, 349–435.
8. Burns M J. Biomechanics. In: McGlamry E Dalton, Ed. Fundamentals of foot surgery. Baltimore: Williams and Wilkins, 1987: pp 111–135.
9. Tiberio D. Pathomechanics of structural foot deformities. Phys Ther 1988; 68: 12: 1841–1849.
10. Sgarlato T E. A compendium of podiatric biomechanics. San Francisco: California College of Podiatric Medicine 1971: pp 60–95.
11. Elveru R et al. Methods of taking subtalar joint measurements - a clinical report. Phys Ther 1988; 68: 5: 678–682.
12. Hicks J H. The mechanics of the foot. I. The joints. J Anat 1953; 87: 354–357.
13. Mann R A. Biomechanical approach to the treatment of foot problems. Foot Ankle 1982; 2: 4: 205–212.
14. Kotwick J E. Biomechanics of the foot and ankle. Clin Sports Med 1982; 1: 1: 19–34.
15. Root M L et al. Biomechanical examination of the foot, Vol I. Los Angeles: Clinical Biomechanics Corporation, 1971; pp 54–72, 116–121.
16. Siebel M O. Foot function — a programmed text. Baltimore: Williams and Wilkins, 1988: pp 15–17, 97–105, 237–243.
17. Spencer A M. Practical podiatric and orthopaedic procedures. Cleveland: Ohio College of Podiatric Medicine, 1978; pp 25, 48–63.
18. Morton D J. The human foot New York: Hafner, 1964: pp 131–140.
19. Barnett C H. The phases of human gait. Lancet 1956; II: 617–627.
20. Wright D G et al. Action of subtalar and ankle-joint complexes during the stance phase of walking. J Bone Joint Surg 1964; 46A: 2: 361–382.
21. Nuber G W. Biomechanics of the foot and ankle in gait. Clin Sports Med 1988; 7: 1: 1–13.
22. Romanes G J. Cunninghams manual of practical anatomy, Vol I. 14th ed. London: Oxford University Press, 1975.
23. Gibbs R C et al. Abnormal biomechanics of the foot and their cause of hyperkeratosis. J Am Acad Dermatol 1982; 6: 6: 1061–1069.

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