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MINI-SYMPOSIUM: THE ELECTIVE FOOT

(i) Relevant foot biomechanics

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foot, ankle, biomechanics, gait, pressure

Summary In order to effectively treat any part of the human musculoskeletal system, it is important to fully understand its biomechanics. Biomechanics is the study of normal mechanics (kinetics and kinematics) in the musculoskeletal system by analysing forces and their effects on anatomical structures. The normal mechanics of the foot and ankle result from the combined effects of muscle, tendon, ligament, and bone. The coordinated and unified effect of these tissues within the foot, ankle and lower extremity results in the most efficient force attenuation. To comprehend biomechanics of the foot during standing and walking, it is important to understand gait. © 2002 Published by Elsevier Science Ltd.

INTRODUCTION

Biomechanics is the study of normal mechanics (kinetics and kinematics) in the musculoskeletal system by analysing forces and their effects on anatomical structures. In order to effectively treat any part of the human musculoskeletal system, it is important to fully understand its biomechanics.

FOOT BIOMECHANICS

The human foot is a complex multi-articular mechanical structure consisting of bones, joints and soft tissues, playing an extremely important role in the biomechanical function of the lower extremity and is controlled by both intrinsic and extrinsic muscles. It is the only part of the body that acts on an external surface, providing support and balance during standing and stabilizing the body during gait. During the stance phase (STP), between heel strike (HS) and toe off (TO), it has to adapt to a changing pattern of loading as the centre of mass of the body moves. An equal and opposite reaction, the ground reaction force (GRF), develops when the foot comes in contact with the ground. The GRF changes in direction and magnitude as the body propels itself forwards (or backwards) (Fig. 1).

The foot must also be relatively compliant to cope with uneven ground, both bare and shod, while maintaining its functional integrity. During ground contact, foot function reverses the convention that a muscle is fixed at its origin and moves from its insertion. The conventional anatomical insertion is often fixed against the ground, and the origin in the heel or leg moves in relation to that fixed point. This provides both flexibility and stability during walking.

The important mechanical structures of the foot include:

1. The bony skeleton, which together with the ligaments and arches, provides relative rigidity and the essential lever arm mechanism required to maintain balance during standing and facilitate propulsion,
2. The joints which confer flexibility,
3. The muscles and tendons which control foot movement.

The foot is the end part of the lower kinetic chain that opposes external resistance.[1] Normal arthrokinematics and proprioception within the foot and ankle influence the ability of the lower limb to attenuate the forces of weight bearing (static and dynamic). The lower extremity should distribute and dissipate compressive, tensile, shearing, and rotatory forces during the stance phase of gait. Inadequate distribution of these forces can lead to abnormal movement, which in turn produces excessive stress which can result in the breakdown of soft tissue and muscle. The normal mechanics of the foot and ankle result in the most efficient force attenuation.

FOOT STRUCTURE

The 26 bones (seven tarsals, five metatarsals, and 14 phalanges) and six joints (ankle, subtalar, midtarsal,

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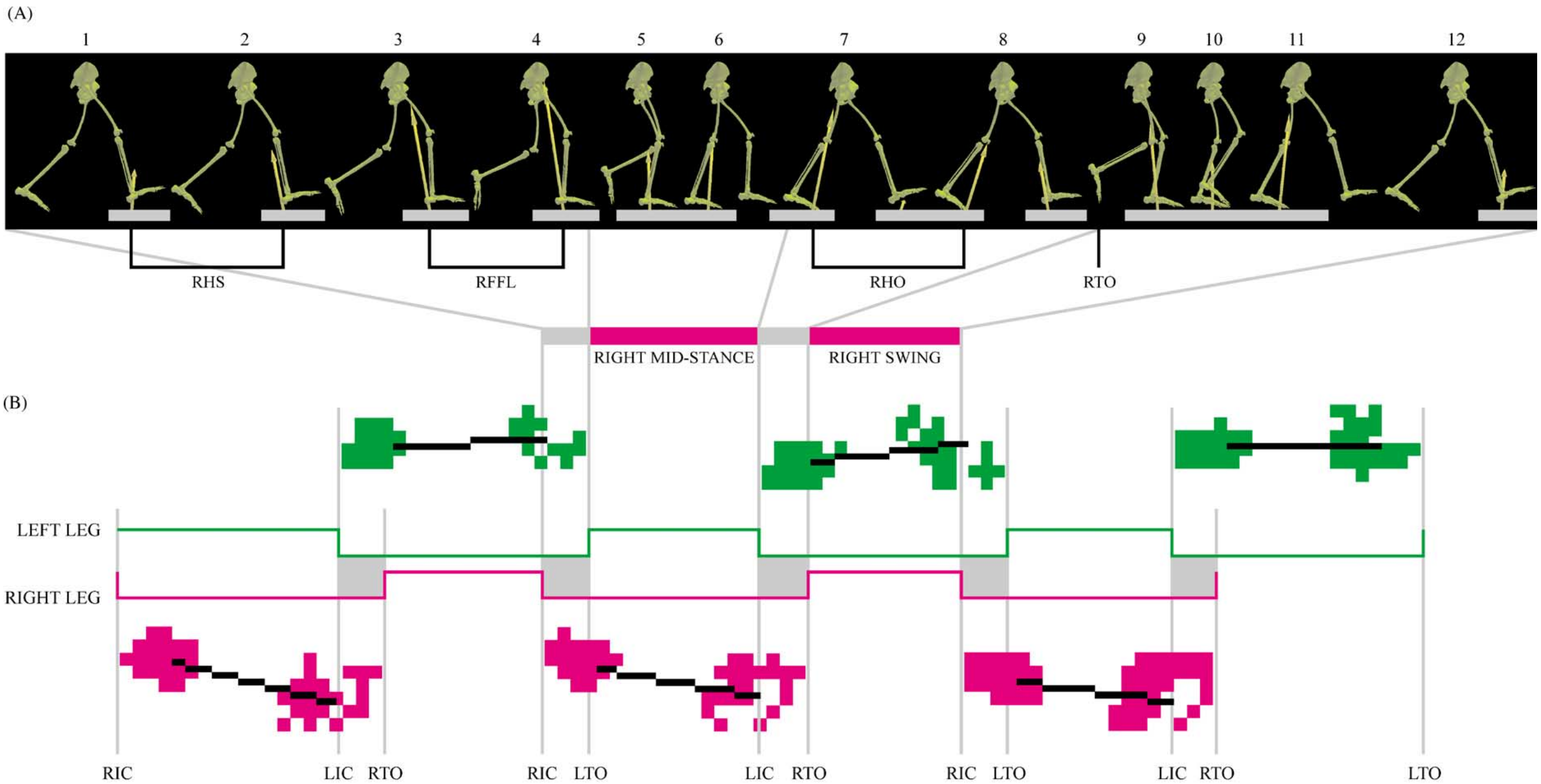


Figure 1 Normal gait cycle: (A) from the Polygon Software (Vicon Motion Systems Ltd®, yellow arrow is GRF) and (B) multiple foot prints from the Gait Rite System® (right (magenta) and left (green)). RIC=right initial contact, LIC=left initial contact, RTO=right toe-off, LTO=left toe-off and RHS=right heel strike, RFFL=right forefoot loading, RHO=right heel off and RTO=right toe off.

tarsometatarsal, metatarsophalangeal (MTP) and interphalangeal (IP) joints) of the foot make up its four segments: the hindfoot, the midfoot, the forefoot and the phalanges (Fig. 2(A)).

The hindfoot

The hindfoot consists of the talus and calcaneus. The three parts of the talus (body, neck, and head) are orientated to transmit reactive forces from the foot through the ankle joint to the leg. Lying between the calcaneus, and tibia, it communicates thrust from one to the other. The calcaneus is the largest and most posterior bone in the foot and provides a lever arm for the insertion of the Achilles tendon, which is the largest and one of the strongest tendons in the body through which gastrocnemius and soleus impart powerful plantarflexion forces to the foot. Its height, width and structure enable the calcaneus to withstand high tensile, bending and compressive forces on a regular basis without damage.

The midfoot

The navicular, the cuboid and three cuneiforms make up the midfoot. The navicular medial to the cuboid, articulates with the head of the talus anteriorly and is the keystone at the top of the medial longitudinal arch. The cuboid articulates with the calcaneus proximally and the fourth and fifth metatarsals distally. The three cuneiforms, are convexly shaped on their broad dorsal aspect whilst the plantar surface is concave and wedge shaped so that the apex of each bone points inferiorly. The cuneiforms articulate with the first, second and third metatarsals distally. This multi-segmental configuration in conjunction with connecting ligaments and muscles contributes greatly to the stability of the midfoot.

The forefoot

There are five metatarsals in the forefoot, these all tapered distally and articulating with the proximal phalanges. The first metatarsal is the shortest and widest. Its base articulates with the medial cuneiform and is somewhat cone shaped. The head of the first metatarsal additionally articulates with two sesamoids on its plantar articular surface. The second metatarsal extends beyond the first proximally, and articulates with the intermediate cuneiform as well as with the medial and lateral cuneiforms in a ‘key-like’ configuration which promotes stability and renders the second ray the stiffest and most stable portion of the foot playing a key role in stabilizing foot posture after hallux surgery.

The third, fourth and fifth metatarsals are broad at the base, narrow in the shaft and have dome-shaped heads. The fifth has a prominent styloid, laterally and proximally at its base, on which the peroneus brevis tendon inserts. Avulsion fracture of the styloid commonly occurs when the foot is inverted against the contracting peroneus brevis muscle.[2]

The phalanges

Phalanges constitute digits. The big toe (hallux) consists of two phalanges, all other toes containing three. The heads of the proximal and middle phalanges tend to be trochlear shaped allowing for greater stability. Functionally, the toes contribute to weight bearing and load distribution and also effect propulsion during the push-off phase of gait.

FUNCTION

Joints of the foot are controlled by extrinsic and intrinsic muscles of the lower limb and provide for the major motion function, angulation and support of the foot. As with all joints, motion occurs by rotation about an axis in a plane of motion. The three planes of motion in the foot are defined as: sagittal plane (Sp), frontal plane (Fp) and transverse plane (Tp).

The foot, or any part of the foot, is defined as being adducted when its distal aspect is angulated towards the midline of the body in the Tp and deviated from the Sp passing through the proximal aspect of the foot, or other specified anatomical reference point. Abduction is when the distal aspect is angulated away from the midline (Fig. 3(A)). The foot is defined as being plantarflexed when the distal aspect is angulated downwards in the Sp away from the tibia, and dorsiflexed when the distal aspect is angulated towards the tibia in the Sp (Fig. 3(B)). The foot is described as being inverted when it is tilted in the Fp, such that its plantar surface faces towards the midline of the body and away from the Tp, and everted when its plantar surface faces away from the midline of the body and away from the Tp (Fig. 3(C)). The foot is considered to be supinated when it is simultaneously adducted, inverted and plantarflexed, and pronated when it is abducted, everted and dorsiflexed (Fig. 3(D)).

With the exception of the midtarsal, MTP and IP joints, the three remaining major joints move in only one plane, i.e. one degree of freedom. The former three joints have two degrees of freedom of motion occurring independently of one another (adduction–abduction/dorsiflexion–plantarflexion).

The ankle joint is the articulation between the distal part of the tibia and the body of the talus, permitting dorsiflexion and plantarflexion of the foot around its axis of motion which passes obliquely in a lateral–plantar–posterior, to medial–dorsal–anterior direction (Fig. 2(B)). The minimum range of ankle joint motion as necessary for normal locomotion is 10° of dorsiflexion and 20° of

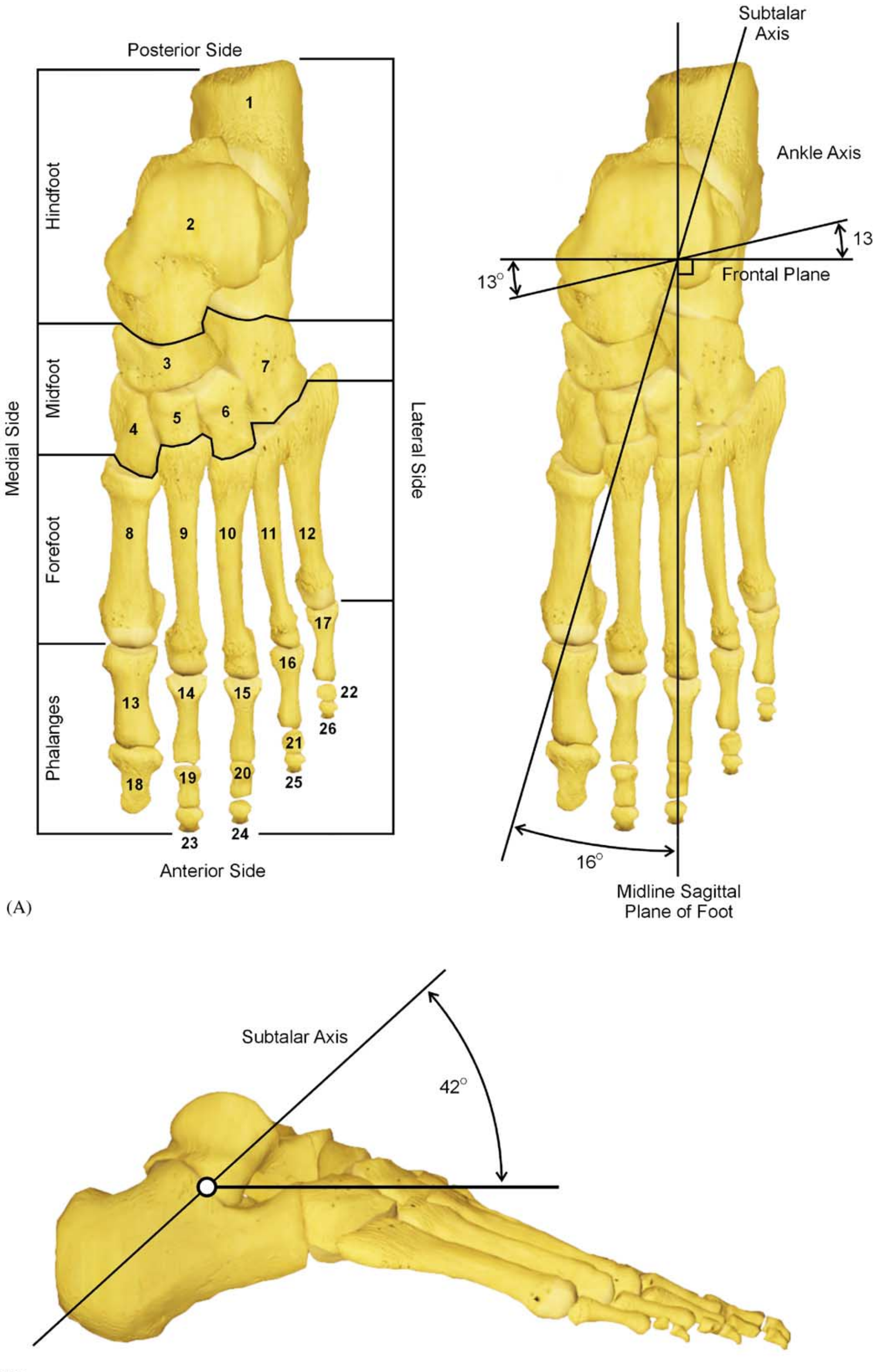
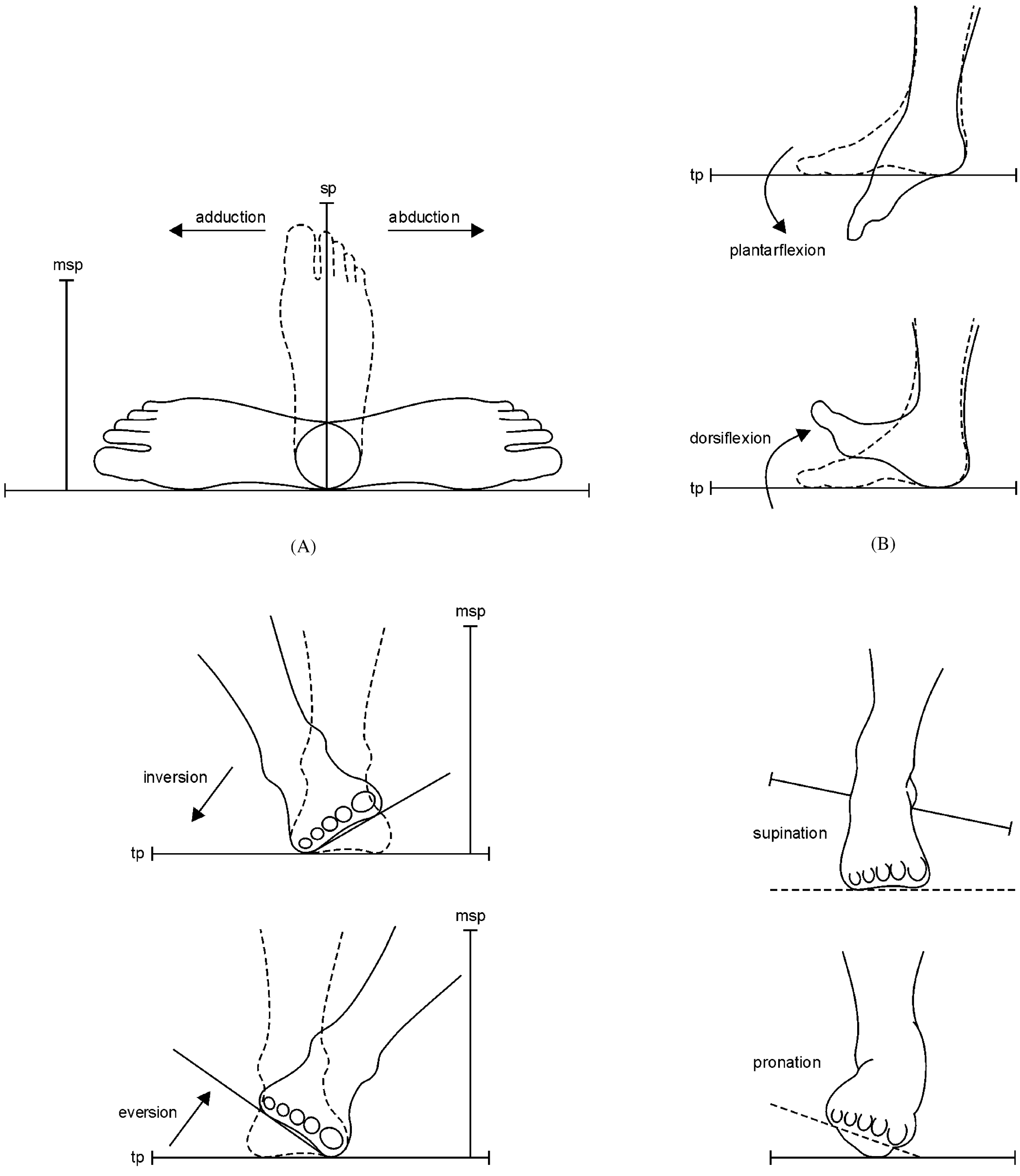


Figure 2 Foot structure: (A) four segments: hindfoot (1, 2), midfoot (3–7), forefoot (8–12), phalanges (13–26), (B) ankle and subtalar axes. 1—calacaneum, 8—first metatarsal, 13—17—proximal phalanges, 2—talus, 9—second metatarsal, 18—distal phalange, 3—navicular, 10—third metatarsal, 19–22—middle phalanges and 4—medial cuneiform, 11 —fourth metatarsal, 23–26—distal phalanges. 5—intermediate cuneiform, 12—fifth metatarsal, 6—lateral cuneiform, 7—cuboid.



(A) (B)

(C) (D)

Figure 3 (A) adduction–abduction, (B) plantarflexion–dorsiflexion, (C) inversion–eversion and (D) supination—pronation.

plantarflexion. The ankle joint also has slight movement in the Tp during plantarflexion, causing instability of the joint in this position.[3]

The subtalar joint includes both the talocalcaneal joint and the talocalcaneal part of the talocalcaneonavicular joint, i.e. it is a composite terminology for the two joints beneath the talus. Its axis of motion passes through the subtalar joint obliquely at approximately 42° from the Tp and 16° from the Sp and resultant motion in Fp[3] (Fig. 2(B)); these motions occur simultaneously. The normal motions exhibited by this joint are supination and pronation.

The talonavicular and the calcaneocuboid joints together form the midtarsal joint. This joint has two axes of motion, an oblique axis and a longitudinal axis which are confined to the talonavicular joint and the calcaneocuboid joint, respectively. Each axis allows movement in one plane only, but because it forms angles to the three body planes, supination/pronation of the forefoot results. The interfaces between the posterior aspect of the metatarsal bones and the lesser tarsus produce the tarsometatarsal joints which have a very limited range of gliding action. The exception to this is the joint between the first metatarsal bone and the medial cuneiform where considerable movement is possible. At the MTP joints, the rounded heads of the metatarsal bones are located in the shallow cavities of the phalanges. Up to 90° of extension is possible at these joints, but only a few degrees of flexion. All of the IP joints allow extension, which is related to abduction, and flexion, which is related to adduction, of the foot.

ARCHES OF THE FOOT

The foot has to both support body weight whilst standing and to act as a lever to propel the body during locomotion. It must be able to conform to even and uneven surfaces, and thus be capable of making good contact with almost any supporting surface, forming a rigid platform that will not collapse under body weight. This is made possible by a series of bony longitudinal and transverse arches (TAs), maintained by ligaments and muscles. The medial arch (MA) comprises the calcaneus, talus, navicular, the three cuneiforms and their three metatarsals. The pillars of the arch are the tuberosity of the calcaneus posteriorly and the heads of the medial three metatarsal bones anteriorly. The lateral arch (LA) consists of the calcaneus, the cuboid and the lateral two metatarsal bones. The MA and LA are relatively rigid in standing but become more compliant during walking; the MA being the more flexible of the two.

A series of TAs exist around the MTP joints, forming a convex curve in the direction of the dorsum when looking at the plantar surface of a non-weight bearing foot. This series of TAs disappear and flatten to varying degrees, during weight bearing. The integrity of the arches is supported by the ligaments, muscles and tendons which provide the combined strength, flexibility and movement necessary for normal function. Their relative importance differs in the three arches; while muscles are indispensable to the maintenance of the MA, ligaments are a relatively more important part in the LA.

MUSCLES OF THE FOOT

The muscles of the foot are essential to maintain the shape of the functional foot. They can be divided into extrinsic muscles arising from the lower leg, and intrinsic muscles arising within the foot itself. These can in turn be divided into dorsal and plantar groups. During locomotion, all of the muscles of the lower limb are actively providing stability and balance during standing, and a strong lever arm effect during propulsion.

BIOMECHANICAL INSTRUMENTATION

Recent advances in computer technology have furthered the understanding of the biomechanical aspects of the human musculoskeletal system by measuring the kinematic and kinetic variables. Kinematics is related to the measurement of motion irrespective of the forces involved using cine/cameras to observe the inter-segmental relationship of the trunk and limbs. Kinetics concentrates on the study of forces associated with motion using force plates, pressure platforms and/or inshoe sensors providing a direct description/orientation of foot posture.

GAIT ANALYSIS

Gait analysis is used by researchers and clinicians to describe an individual's pattern of walking. In modern rehabilitation, there is an increasing need for objective and quantitative measurement of the relevant aspects of gait. This should ultimately lead to a better understanding of inter-related foot/limb function. Gait analysis also involves the measurement of muscle activity, and both kinetic and kinematic elements during gait. Most of the problems associated with foot disorders are in one way or another related to the weight-bearing process at the foot–ground or foot/shoe–ground interface.

Gait cycle (GC)

During normal walking, one full GC is referred to as the time interval between two consecutive heel strikes of the same foot (Fig. 1(A):1–12 and 1(B):RIC–RIC) on the ground. This time interval is known as the stride time. Stages of a GC are shown in Fig. 1(A and B) and are marked for the right side: heel strike (RHS), forefoot loading (RFFL), midstance (RMS), heel off (RHO) and toe off (RTO). The GC is divided into two major parts: the stance phase (STP) and the swing phase (SWP), these representing the weight and the non-weight-bearing periods for the foot and on average last for about 60% and 40% of the gait cycle, respectively. The double support period, which on average lasts 10% of GC and occurs twice in any one GC, indicates that both feet are in touch with the ground.

Ground reaction force

The GRF magnitude, direction, point of application, and the way in which it is spatially distributed over the plantar surface of the foot during gait is of great relevance to both the assessment and any subsequent treatment plan for the lower limbs. The GRF is counteracted and controlled by the function of the lower limb muscles which, in conjunction with the bones, joints and tendons of the foot, controls the kinetic and kinematic progression of foot with the ground.

The foot in gait

During locomotion, lower limb muscles act in concert with each other as either synergists or antagonists and have primarily two functions: to stabilize, and accelerate/decelerate the foot during both the weight-bearing and propulsion phases of gait. Some muscles have more than one function. For example, the long extensors first stabilize the joints of the toes during propulsion, then serve as accelerators in ankle joint dorsiflexion following toe off, and finally assist as decelerators of the foot at HS. To give an example, the tibialis anterior decelerates the foot following HS, and then accelerates to assist in ankle joint dorsiflexion following TO. Consequently, the different phases of gait are therefore described in relationship to lower limb muscle activity.

Heel strike

At HS, and for a very short period immediately thereafter known as the transient period, the GRF is anterior to both the ankle and knee joint and lasts between 10 and 20 ms[4] (Fig. 1(A:1)); this can be measured using a force plate and linked video camera array, e.g. the Vicon System.[5] The location of the GRF then changes immediately after HS to a location posterior to both joints (Fig. 1(A:2)), creating an external plantarflexion moment around the ankle joint. At this instant, the tibialis anterior, with assistance from the extensor hallucis longus muscle, contracts eccentrically, producing an internal dorsiflexion moment which decelerates the rate of ankle joint plantarflexion.[6–8] The combined synergistic action of these two muscle groups allows the foot to passively plantarflex in a smooth, regulated manner such that ankle joint plantarflexion is virtually stopped synchronously with the forefoot making contact with the ground. This control effect avoids the sudden 'slapping' of the forefoot on the ground, which can, in some cases, produce considerable forefoot trauma.[3] The tibialis anterior muscle has been a favoured object of study over the years and the use of cinematography[9] has demonstrated that the subtalar joint is inverted and the ankle is dorsiflexed at the moment of HS and the leg is internally rotated. More recently, the tibialis anterior muscle was demonstrated to be subject to a statistically significant delay of 180 ms ($P < 0.001$) in diabetic subjects when compared to a normal control group.[10] This late firing means that the normal modulating role of the muscle in lowering the foot to the ground after HS is disturbed, leading to forefoot slap and subjecting it to high plantar pressure. If the HS can be delayed and foot slap prevented, a restoration to the normal foot–ground approach can be achieved and would be compelling evidence of the true aetiology of high forefoot plantar pressures in diabetic subjects. This would also provide a simple and effective preventive method of reducing morbidity in diabetic patients.

Forefoot contact and MS

During the initial movement of the forefoot only the lateral side of the forefoot makes contact with the ground. As weight is transferred to the forefoot, the effect of the GRF on the lateral side of the forefoot tends to evert the forefoot against the resistance caused by the contraction of tibialis anterior. The controlled relaxation of the tibialis anterior facilitates smooth progressive loading of the forefoot from lateral to medial locations. This is achieved by gradually decreasing the resistance to pronation of the forefoot around the longitudinal axis of the midtarsal joint. The tibialis anterior then relaxes and goes silent until the TO phase of gait. Therefore, the GRF gradually everts the forefoot until full foot contact is achieved; loading of the forefoot is then transferred from the lateral to medial side.[7] Following HS and before forefoot contact, the calf muscles, i.e. the tibialis posterior, with soleus and gastrocnemius, begin to contract. These muscles, which function to collectively decelerate subtalar joint pronation and internal leg rotation, continue to contract throughout the MS phase and relax at HO or very shortly thereafter[6,8,9] (see Fig. 4). During forefoot loading, the GRF maintains its posterior direction (Fig. 1(A:3–4)), but with an increasing magnitude until MS, where it begins to move anteriorly along the foot. This causes the GRF to become smaller and to ultimately reverse in direction (Fig. 1(A:5–7)). At this point, the GRF is still posterior to the knee joint but becomes anterior to the ankle joint (Fig. 1(A:5)). At the beginning of the MS period, the posterior calf muscles become prime movers which initiate subtalar joint supination and external leg rotation. Both the tibialis posterior and the soleus have attachments which create significant lever arms relative to the axis of motion of the subtalar joint.

The forward momentum of the tibia over the foot which is fixed on the ground produces ankle joint dorsiflexion. After forefoot contact, the ankle is plantarflexed, and following this, the ankle joint begins to dorsiflex as the tibia moves forwards, over the foot. The tibia continues to move forward, causing ankle joint dorsiflexion throughout the MS period until the point of HO. Deceleration of forward tibial momentum also extends the knee in preparation for HO. The muscles which decelerate the forward momentum of the tibia to assist in knee extension are those which have significant lever

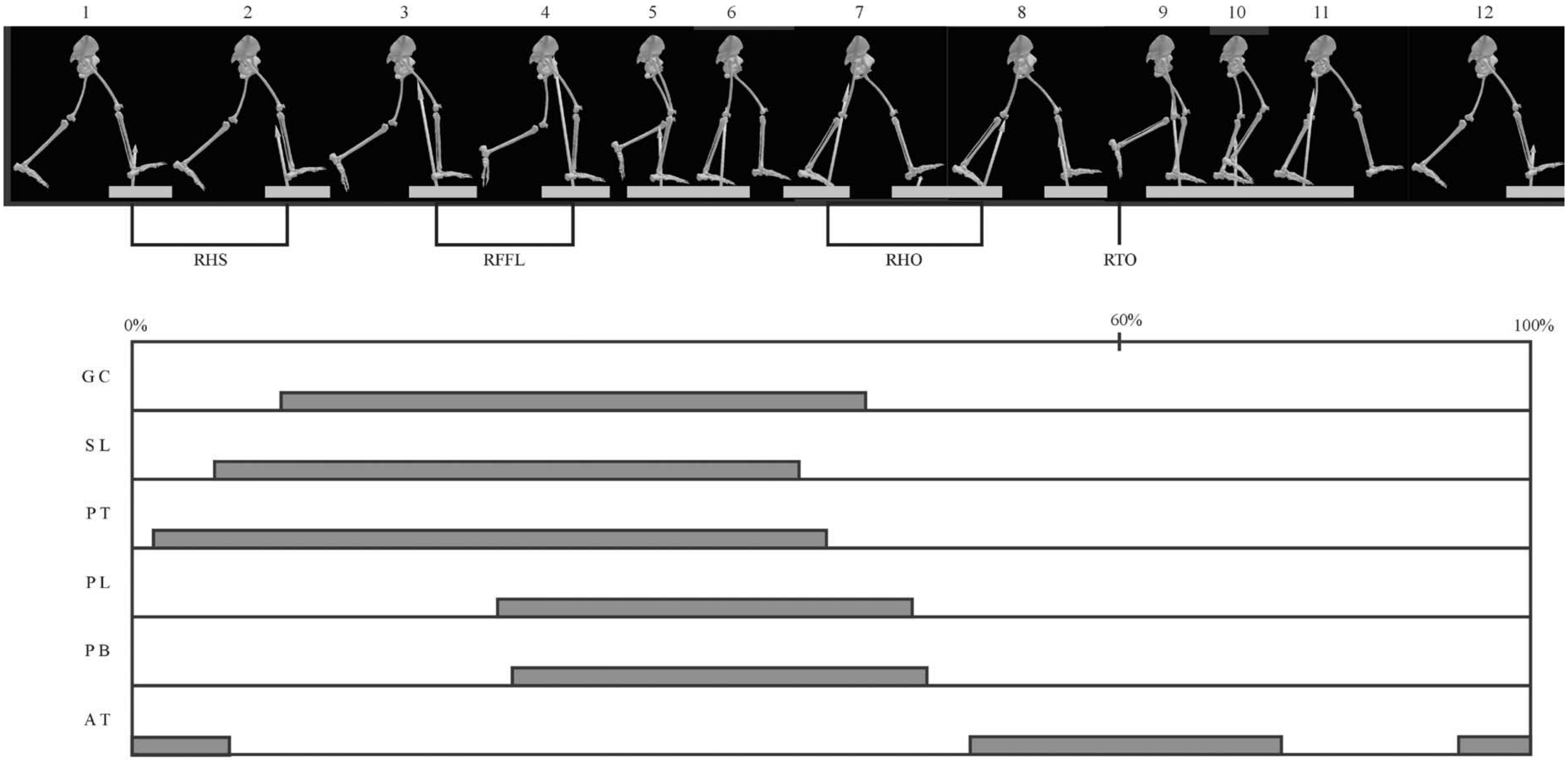


Figure 4 Timing of six muscles activity during walking. GC=gastrocnemius, SL=soleus, PT=tibialis posterior, PL=peroneus longus, PB=peroneus brevis and AT=tibialis anterior.

arms for ankle joint plantarflexion. These muscles are: tibialis posterior, soleus, and flexor digitorum longus, with also some late MS assistance from peroneus longus. Gastrocnemius is also an ankle joint plantarflexor; however its femoral origin provides it with an antagonistic function relative to the other calf muscles.

The bones of the lesser tarsus are stabilized during the MS period as follows: in early MS, soleus, tibialis posterior, peroneus longus, and peroneus brevis muscles are responsible for this stabilizing effect. The lateral side of the foot must be stabilized against the ground before the individual bones of the lesser tarsus can be stabilized in the Tp. The soleus maintains the Sp stability of the cuboid in order to serve as an effective pulley for the function of peroneus longus. Peroneus longus pulls the first ray laterally against the lesser tarsus, whilst the tibialis posterior pulls the lesser tarsal bones medially.

Collectively, the effects of these opposing actions serve to compress the lesser tarsus in theTp, thus producing medio-lateral stability. The magnitude of the adduction force generated by the tibialis posterior exceeds that of the abduction force exerted by the peroneus longus. Consequent to this, peroneus brevis exerts an additional abduction force upon the lesser tarsus to thereby neutralize the otherwise existing imbalance. Therefore, peroneus brevis complements the function of peroneus longus to help in maintaining the transverse stability of the lesser tarsus during the stance phase. The forefoot cannot abduct at the midtarsal joint beyond the normal locking point of that joint, which is reached when it is fully pronated. Further abduction of the forefoot is facilitated by pronation of the subtalar joint. In disorders, such as cerebal palsy, the entire foot may be pronated into a flat foot position; this is described clinically as the peroneal spastic flatfoot.[11]

Heel-off and propulsion phase

At HO, also known as heel rise, the GRF is anterior in relation to both ankle and knee joints creating an external dorsiflexor moment which is opposed by both the soleus and gastrocnemius muscles (Fig. 1(A:6–8)). The peak activity of these muscles coincides with the peak external moment occurring just after HO. The metatarsals must become stable before they can assume their weight-bearing function during propulsion. Following HO, the foot momentarily bears full body weight alone. Simultaneously, the vertical GRF generated exceeds that of bodyweight and, moreover, the ball of the foot is also subjected to torque and high shear forces. The major function of the intrinsic muscles during the second half of the MS phase is devoted to providing the tensile forces necessary in stabilizing the bones of the metatarsus and lesser tarsus transversely and posteriorly against one another. When the foot is abnormally pronated the intrinsic muscles must function longer and stronger during the MS period. Tension forces are increased when the foot is abnormally pronated, and this tension increases when the joints of the skeleton are also subluxed. Therefore, economy of intrinsic muscle function, during the MS and propulsive periods is dependent upon supination of the foot.[12]

Heel rise results from an interaction between forward momentum of the body, deceleration of the tibia, and passive knee flexion. At the end of MS, the trunk is directed forwards relative to the foot, and the body is falling forwards over the weight-bearing foot. Forward trunk momentum carries the thigh and leg with it. The knee extends during MS, but immediately prior to heel rise the knee begins to flex. Thereafter, the tibia continues to move forward while the heel rises, as evidenced by maintaining ankle dorsiflexion into the early propulsion period. The muscles which are primarily responsible for the tibial deceleration are tibialis posterior, gastrocnemius and soleus with later assistance from the flexor digitorum longus and peroneus longus.[3] Just before commencement of heel rise, contraction of the gastrocnemius muscle halts knee extension and then begins to flex it.

During the propulsion phase, the ankle initially dorsiflexes slightly, and then plantarflexes until TO. Shortly after heel rise, ankle dorsiflexion is stopped consequent to the weight no longer passing through the heel. At this time, the calf muscles, which previously decelerated the forward momentum of the tibia and rate of ankle dorsiflexion, now begin to plantarflex the ankle joint. During the early stage of the propulsion phase, gastrocnemius, soleus, peroneus longus and possibly tibialis posterior all contribute to ankle joint plantarflexion. During propulsion, only one muscle, the transverse pedis, more properly called the transverse head of adductor hallucis, appears to have the necessary requirements for the transverse stabilization of the forefoot.

Shortly after heel rise, the lateral side of the foot lifts from the ground. Weight is transferred to the medial side of the forefoot where it normally concentrates on the great toe during the final stages of propulsion.[7] The two muscles which primarily involved in this propulsive event are: peroneus longus and brevis (Fig. 5).

During normal propulsion, the lesser toes are stabilized against the ground, and each toe is extended at each of the IP joints. The long and short plantarflexors of the lesser digits stabilize the toes against the ground, but they cannot do so unless the toes are first converted into rigid beams by the extensor mechanism. The following factors influence propulsion phase stability of the great toe: stability and plantarflexion of the first ray, normal sesamoid function, normal strength and function of the muscles responsible for hallux, and first MTP joint stability.

Reduced efficiency of any of the preceding factors reduces the effective potential for the hallux to bear weight during propulsion. The hallux must be completely stable before it can bear its share of the load during propulsion. When it is not stable, either part or all of the load it normally supports must be supported by the second or third metatarsal heads. The hallux cannot be stabilized adequately unless the first ray is also stable and the sesamoids are normally positioned under the first metatarsal heads. The hallux must also be able to dorsiflex 65–70° on the first metatarsal,[13] during final propulsion, or it will sublux at the first MTP joint and become unstable. This full dorsiflexion range of the hallux can only be achieved when the first ray plantarflexes during propulsion.

Toe-off and swing phase

Just prior to TO, the GRF is still anterior to the ankle joint but has moved posterior to the knee joint. The tibialis anterior begins to contract immediately before TO until midswing, thus creating a rather smaller dorsiflexor moment around the ankle joint which helps in clearing the foot off the ground (Fig. 1(A:9)). The foot then enters the SWP and the GRF disappears until the following HS (Fig. 1(A:12)).

Gait analysis instrumentation

Gait analysis laboratories use reflective markers and/or high-technology equipment such as powerful low/high frequency cameras along with compatible software for the analysis and presentation of motion (e.g. Vicon System[5]). They have not been proven to be cost effective and have been the topic of debate in recent national and international conferences.[14,15] Additionally, the type of analysis is dependent on the type of equipment available, the expertise of the user and the space available (130 m^2 to accommodate the cameras in a format to produce three-dimensional gait analysis is required). On average, upto $1\frac{1}{2}$ h is needed per subject to record the gait data.

In the last decade or so, a new portable gait analysis system (e.g. GaitRite[16]) appeared on the market providing the user with an automated means of measuring the spatial and temporal parameters of gait. These systems complement the former generation and are portable, relatively cheap, easy to use and provide an almost complete analysis instantaneously. They are very useful when dealing with patients with 'shuffling' gait and low assessment tolerance, for example those suffering from Parkinson's disease. The primary disadvantage is however their incompetence in providing inter-segmental relationship which is sometimes crucial when assessing patients with cerebral palsy.

Pressure analysis systems

As shown in Fig. 1(A), the GRF changes in direction and magnitude as the body propels itself forward. This force is proportional to infinite discrete areas on the plantar surface of the foot when in contact with the ground and is described as foot pressure. Gait and pressure systems have often been thought to be the same but this is not the case. In the latter case, the body weight is distributed over infinite discrete points on the plantar surface of the foot, and indicates gait cycle (mainly the inshoe systems), pressure points, gait pattern, foot print and posture, and centre of pressure. The former provides inter-segmental relationships between the various parts of the body (foot, lower leg, thigh, spine, etc.) but gives no indication of pressure distribution over the plantar surface of the foot.

Over the last two centuries, many attempts have been made to develop a suitable technique to measure the pressure distribution underneath the plantar surface of the foot. The range of techniques and equipment currently available vary from the cheap and simple (e.g. Harris & Beath mat and the Podotrak) to extremely complex and expensive devices. Most are capable of only measuring the vertical pressure despite ongoing work in various centres to develop the ultimate shear plus vertical sensor.[17] The choice of a system should depend heavily on the precise measurements needed, bearing in mind the five most important characteristics when choosing a system: range, reliability, reproducibility, frequency response and resolution, not to mention being user-friendly.

As an add-on to gait and pressure measurement devices in understanding the biomechanics of the foot/ankle, the following devices can also be considered of importance: portable electromyography,[8–10] goniometry,[18] and energy expenditure.

FOOT/ANKLE PROPRIOCEPTION

Foot/ankle proprioception is the awareness of the position and motion of the foot joints in space with the ability to accurately match reference joint angles without visual feedback. Any excess or limitation of motion in the subtalar complex will tend to have implications proximally, for the lower limb, and distally for the foot.[18] Ankle injuries are among the most common injuries in physically active people and vary from mild ligamentous sprain to severe disruption of the articular surfaces with extensive soft tissue damage. Of all the time lost through injury in running and jumping sports, 20–25% involves the ankle.[19] In considering ruptures of the fibular collateral ligament, it was suggested that functional instability was due to mechanical instability, peroneal weakness, tibio-fibular strain and proprioceptive deficit. Injuries occur when a force, applied to the foot, is transmitted through the talus displacing it beyond the normal elasticity of the ankle ligaments. If the force is axial in nature, fractures of the tibial plafond occur (the so-called pilon fracture) with variable degrees of compression. If the force involves less axial load but more rotational movement of the talus on the tibia, malleolar fractures occur. Hence, traumatic disorders of the ankle occur as the result of one, or a combination of two, of the following foot movements: internal rotation, external rotation, abduction and adduction.[20]

Various extrinsic and intrinsic factors have been considered to be potential risks for ankle injuries. Extrinsic factors include training errors, type of activity (e.g. sport), exercise time, equipment and environmental conditions. Among the intrinsic factors, it was found that height, weight and previous history of ankle sprain had a significant relationship with the incidence of lateral ankle sprain.[21] In addition, individuals with muscle strength imbalance in the form of elevated eversion-to-inversion strength ratio and greater plantarflexion strength had a higher incidence of inversion ankle sprain.[22] Recently, a direct method for quantitative measurement of ankle proprioception using a three-dimensional electromagnetic goniometer system, the Isotrak®, with a view to assessing the role of proprioceptive deficits and various risk factors in the aetiology of ankle injuries was developed.[18] Measurements were based on the ability of subjects to accurately match reference joint angles without

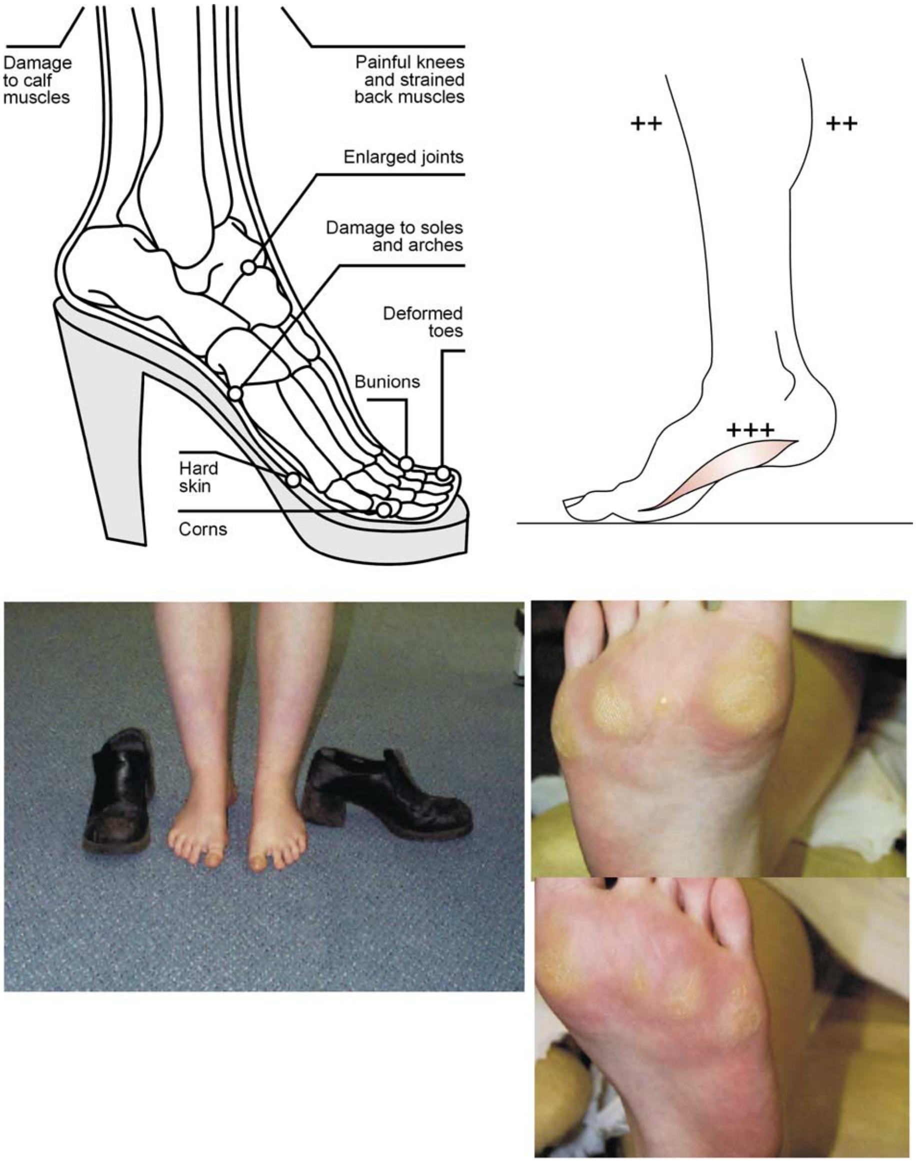


Figure 5 Effect of high heel shoes on feet ('+' sign indicates active muscle function during standing).

visual feedback. Further work, yet unpublished, was carried out showing that footwear alters normal volunteers foot/ankle proprioception and this was also demonstrated in patients who had suffered previous ankle injuries. Ankle injuries are fewer in unshod populations suggesting shoes may alter the ability of the protective mechanisms around the ankle in preventing damage. This may be due to increased leverage at the ankle confirmed by the unnaturally high heel and reduction of foot/ground sensation. Equally, it may be that a foot held in a firm heel counter might modify proprioceptive sensation around the ankle/heel complex. As foot/ankle injuries occur mainly under dynamic activities, current work is now being focussed on measuring ankle proprioception during walking. The deceptive advertising of expensive athletic shoes to safeguard feet through 'cushioning impact' which accounted for 123% greater injury frequency of the lower extremity than the cheapest shoes was highlighted in a recent article.[23]

CASE REPORTS

In addition to clinical and biomechanical assessments, knowledge of functional orthoses and footwear mechanics is important to provide a comprehensive treatment modality, not to mention that common sense should prevail. Since its inception in 1993, most patients seen at the Foot Pressure Analysis Clinic (FPAC) in Dundee, regardless of how minor or complex their problem was, were using ill-fitting footwear with discrepancies in-shoe width and size when compared to their feet. In some cases, there was a difference of up to 3 UK sizes and 4 cm in width across the metatarsal head area, needless to say causing abnormal biomechanical forces through the foot joints. The cumulative damage caused by footwear over the years goes in most cases unnoticed and gets ignored despite clear signs of pain and dorsal callus formation, the latter can only develop as a result of friction with the inner shoe. The damage becomes multi-compound when using high-heel shoes causing an instant forward shift of the centre of mass, resulting in increased pressure under the metatarsal heads and toes, abnormal joint and muscles function within the foot and lower leg and ultimately balance, proprioception and body posture (Fig. 5). Below are three cases recently treated at the FPAC.

Case A. A patient suffered fractures of the proximal phalanges of the second and third toes of the right foot and third metatarsal shaft. On reviewing at one year, the fractures were well healed (Fig. 6(A and B)) but left the patient with forefoot pain on the plantar and dorsal aspect of the third metatarsal head during walking.

As the pain was present both bare and shod, this excluded any effect the shoes might have had in causing pain. Assessment was focussed on the foot biomechanics. While the weight-bearing X-rays did not in the first instance show any clinical abnormality, foot pressure assessment (Fig. 6(C)) showed that there was relatively very low pressure underneath the third metatarsal head (circle 5) when compared to the adjacent second and fourth leading to the conclusion that the third shaft healed in an abnormally dorsiflexed position (Fig. 6(B) red arrow) which caused a neuroma and hence the pain. The neuroma was excised and the right foot was supported with a custom-made insole to compensate for

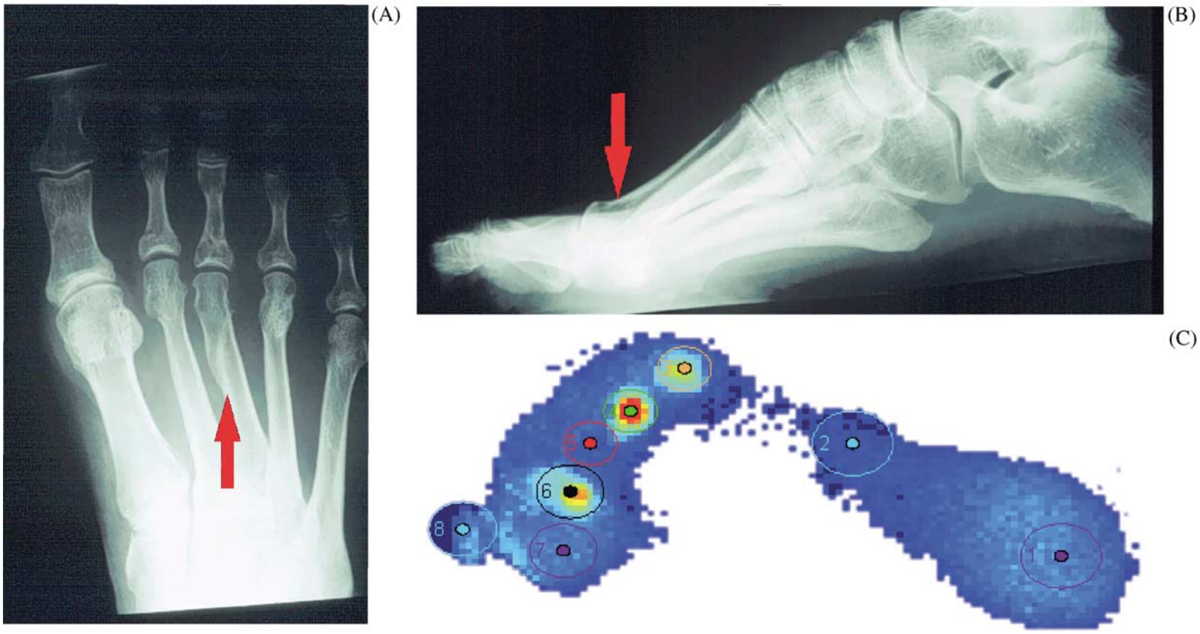


Figure 6 Case A: (A) A/P weight-bearing X-ray, (B) Med/Lat weight-bearing X-ray and (C) dynamic foot pressure print.

the abnormal pressure distribution and abnormal third metatarsal shaft. The patient is currently seen for insole replacement, otherwise discharged from regular clinical/biomechanical review.

Case B. A female patient with metatarsalgia who had previously been treated with five different sets of insoles (Fig. 7(A)) was randomly selected from the Orthotic Department database. She agreed to participate in a retrospective foot pressure measurement study. She hoped that the measurements would improve the management of pain under the ball of her feet as the insoles she had received over the years had aggravated rather than relieved her symptoms. Her symptoms started 20 years ago shortly after bilateral hallux fusion surgery which inevitably shortened the first rays (Fig. 7(B)). Despite the pain felt under the ball of her feet, there were no signs of callus formation. This coincided with the relatively low dynamic pressure values recorded with the Optical Dynamic Pedobarograph. However, when compared to the hallux and first metatarsal head pressure values, foot pressure analysis showed higher pressure values under the lesser toes and their respective metatarsal head on both feet (Fig. 7(C)). This is a clear indication that at push off the forefoot is supinating as a compensatory measure to the shortening of the first rays.

The insoles previously provided incorporated a bar or dome which aggravated the pain. She was treated symptomatically rather than for the primary cause which was increased pressure under the lesser toes. The dome/button elevated the second, third and fourth metatarsal shafts which further extended the lesser toes and in turn increased the pressure under them, hence the failure in the past orthotic management.

The insole should incorporate internal transverse and longitudinal rockers with cushioning under the lesser toes. The transverse rocker facilitates the transfer of load from the lateral to medial aspects of the foot whilst the longitudinal rocker compensates for the first ray shortening and assists at the push off stage (Fig. 8).

Case C. A patient aged 52 years was referred for biomechanical and foot pressure assessment in late 2000 with 'diffuse midfoot pain affecting the plantar aspect of his right medial arch' (Fig. 9(A)). He had had tarsal tunnel

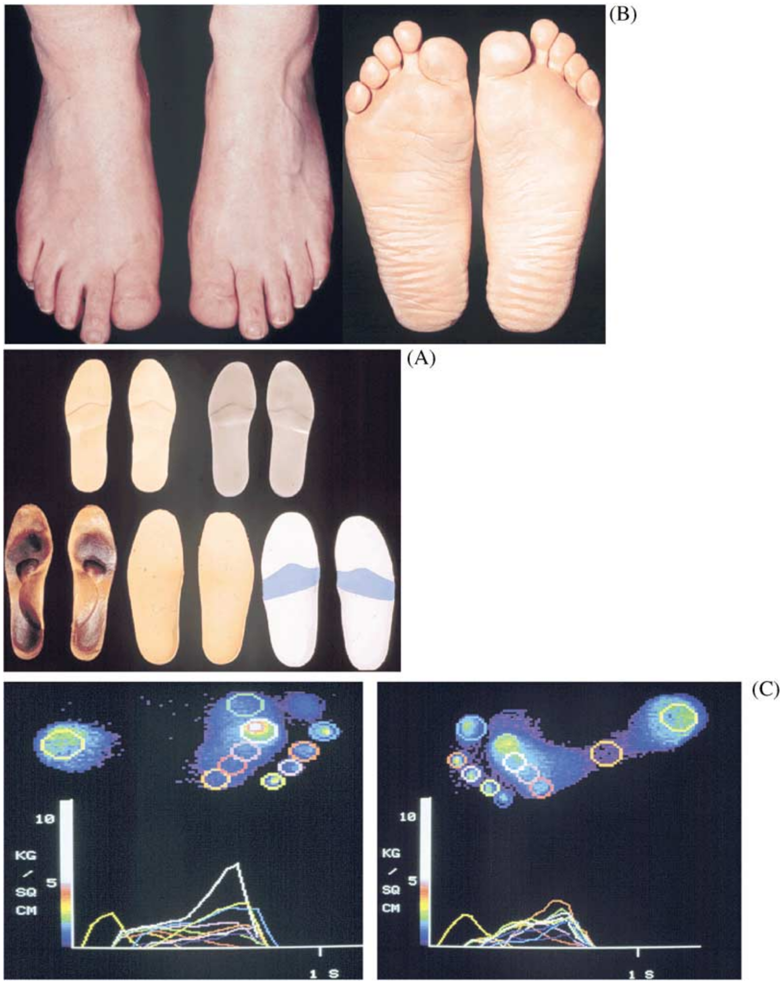


Figure 7 Case B: (A) insoles provided, (B) patient's feet and (C) patient's dynamic pressure prints and pressure–time graphs.

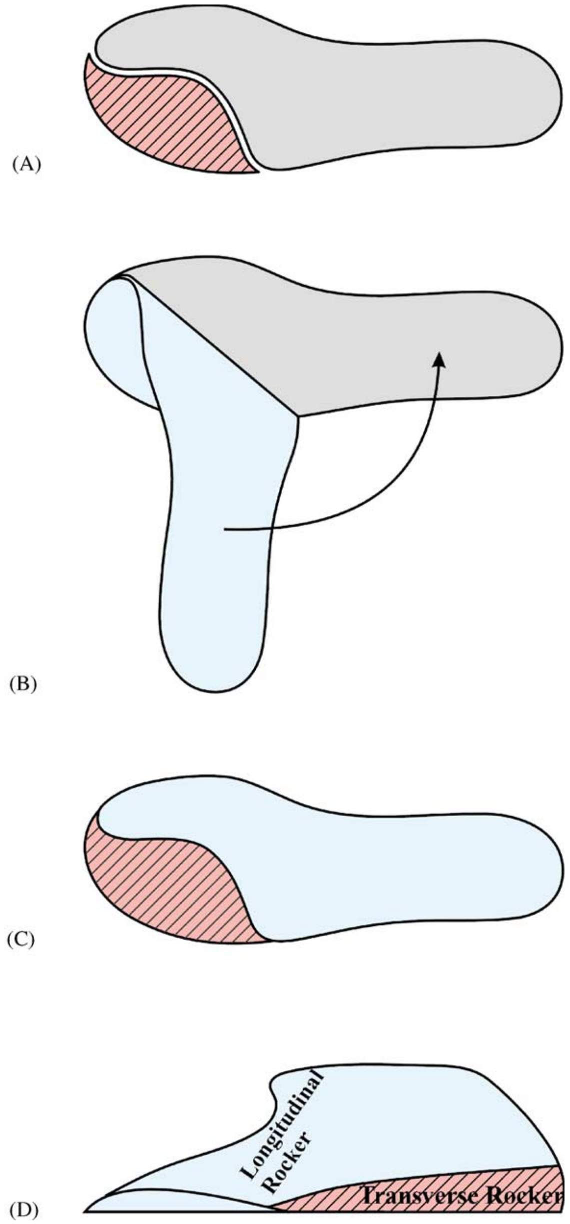


Figure 8 Schematic of a composite insole incorporating an internal transverse and longitudinal rockers. Grey colour indicates the semi-flexible carbon fibre base and the shaded pink area represents the transverse rocker consisting of soft (gelly) material.

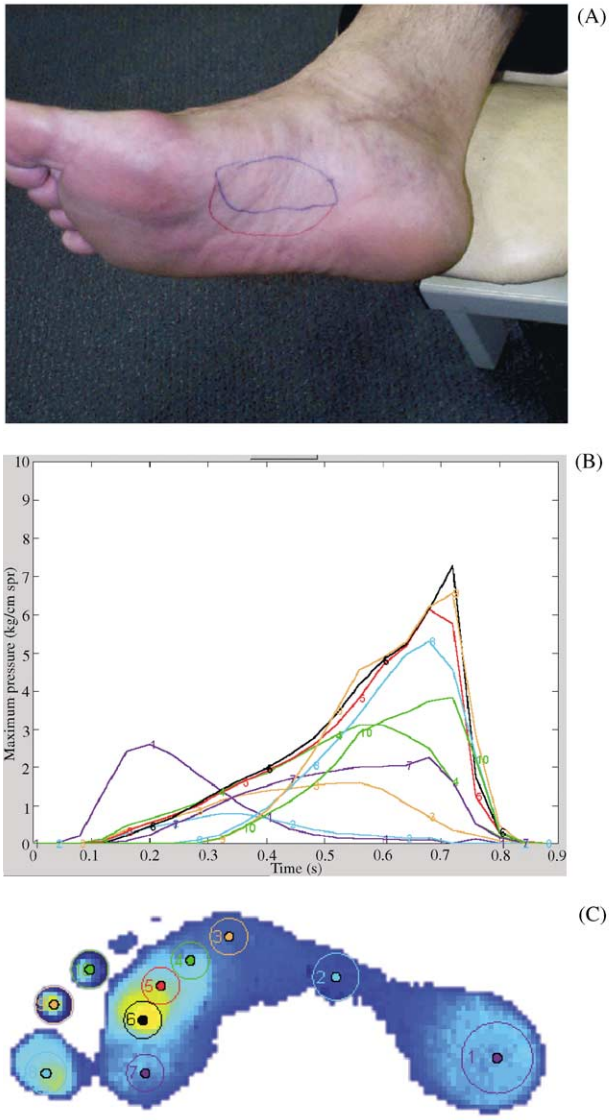


Figure 9 Case C: (A) area of pain, (B) pressure–time graph and (C) dynamic pressure print.

surgery exploration in 1999 which failed to improve his symptoms which started in 1992.

Following biomechanical assessment and foot pressure studies, the latter showing no signs of abnormalities, the problem was localized around the midpoint of the flexor hallucis longus (FHL) tendon, which upon pressure caused severe pain shooting up the leg through the FHL tendon/muscle. In addition, it was interesting to note that he experienced minimal or no pain when walking barefoot or when using his working boots which incorporated a dorsal metal cup and a plantar steel bar, the latter providing an external rocker mechanism. His pain was only experienced when wearing formal leather shoes size 10 UK compared to his foot sizes of $9\frac{1}{2}$ (left) and $10\frac{1}{2}$ (right). The shoes being smaller than his right foot caused abnormal longitudinal forces along the first ray in addition to the irritation caused by the built-in arch.

As a temporary solution, the built-in arch was removed and a semi-flexible carbon fibre insole inserted in his current shoes to provide him with an internal rocker to overcome the action of the FHL until the 8 years of accumulated inflammation had eased off. He was advised to purchase a sturdy pair of shoes matching his foot sizes, preferably with a rubber sole, and to transfer the carbon insole over.

Four days later, an e-mail was received from the patient saying 'after my visit to your clinic, I immediately bought a pair of boots and transferred the temporary insole. The discomfort has drastically reduced and the pain has subsided. . ..'

If the question 'do you have pain when walking barefoot?' had been asked over the eight years period of investigation, it could have saved the patient pain and an unnecessary surgery, and the health service money!

CONCLUSION AND PRACTICE POINTS

It is very important to complement the clinical assessment by a biomechanical one:

- Clinical assessment
- Biomechanical assessment
- Appropriate treatment
- Avoid TRIAL & ERROR management
- Always try to find the primary cause of the problem
- Never treat the secondary symptoms without knowing the primary cause
- Try not to ignore any detail, no matter how irrelevant you might think

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