UNDERSTANDING THE MECHANISMS AND FUNCTION

OF THE HUMAN FOOT

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An Introduction to a New Concept

To date surgeons and anatomists have not fully understood the functional mechanisms of the human foot, and frequently the coordinated movements at the inter-tarsal joints have been thought of, and described, as ‘being too difficult to understand’. Several concepts have been previously put forward.

With the aim of understanding foot function we have designed and carried out various studies in Newcastle during the past 20 years. In 1993 the forefoot transverse tie-bar was described in a Hunterian Lecture (Stainsby 1997), and further results relating to the coordinated movements of the tarsal joints were presented in a Royal College of Surgeons ‘Arnott Lecture’ in 2004.

Since then Professors Bertil Romanus (Göteborg), Hans Zwipp (Dresden) and Roger Atkins (Bristol) have shown helpful interest and provided constructive comment and encouragement. Presentations of the Newcastle ‘hypothesis’ with supportive evidence have been given in Sweden, Germany and Bristol. The new concepts are initially not easy to understand within a short presentation as description of three-dimensional movements is difficult. This is an ’introductory outline’ that presents the main underlying ideas, and it is hoped that it will be helpful.

Some earlier concepts and theories, and the previous work of Hicks, de Doncker and Kowalski, Ambagtsheer, and Huson, and those associated with the stereophotogrammetric studies of the foot (Van Langelaan, Lundberg et al, Winson et al) are reviewed, and I have tried to show how their conclusions can be incorporated into a different approach to the understanding of foot mechanics and control. Basically, the recommendations of Professor Huson have been followed – that movements at the intrinsic joints of the foot should be related to the shape and contour of the articular surfaces and the restrictive/controlling effect of their related ligaments, rather than think of movements taking place about multiple but specific axes. Calculated ‘axes of rotations’ can demonstrate the relative pattern of movement between parts of the foot, and even between individual bones, but they do not provide an explanation for the observed three-dimensional motions – they do not represent actual ‘hinges’ within the skeletal structure.

The attached ‘powerpoint presentation’ illustrates the main principles, and a list of references is added here that may assist as preliminary reading and background information, and so help provide a basis for discussion. It is suggested that if easily available the paper by Ambagtsheer is probably the most important to be read – particularly the section where the results of investigations into the coordinated movements of the three major inter-tarsal joints are presented. It is the only source of information that I have found for measured and recorded movements at the calcaneo-cuboid joint

Nomenclature

The terms supination and pronation are preferred to inversion and eversion for describing movement around the longitudinal axis of the foot (**slide 2**).

A ‘New Approach’ to understanding foot mechanics (slides 3 – 4)

The ‘new approach’ is based on:

(i) The concept that a multi-segmental ‘ligamentous’ tie-bar support system is a major control mechanism for foot structure support and stability, the function of the toes and the plantar pad, and

(ii) The hypothesis that the design of the human foot, with its **lateral swing** movement at transverse tarsal joint level, enables it to function as a ‘balanced cantilever’ and provide a lateral balance mechanism

THE LONGITUDINAL STRUCTURE OF THE FOOT

A. The longitudinal foot structure and the ‘3 arches’ concept (slide 5)

Previously the foot has often been thought of as having ‘3 arches’:

A medial longitudinal arch (or column)
A [lower] lateral longitudinal arch (or column)
A transverse arch at the level of the MT heads (or half a transverse arch at mid-foot level)

But: an ‘arch construction’ requires foundations so that within the curved structure the ‘wedge-shaped’ bones [or stones] can support each other by mutual pressure, and the bases of the structure do not move apart with load-bearing.

The term ‘arch’, applied to the longitudinal foot structure, is therefore technically inappropriate.

B. The concept that the longitudinal structure of the human foot has a ‘bow-string beam’ construction and the importance of the windlass mechanisms of the plantar aponeurosis (slides 6–9)

Hicks (1954 and 1955) elegantly demonstrated the importance of the plantar aponeurosis – attached proximally to the plantar tuberosity of the calcaneus and with five strong processes extending forwards to be inserted into the plantar plates of the MTPJs, and thereby to the bases of the proximal phalanges of the 5 toes. The resulting ‘tie-bars’ prevent the curved (‘arch-like’) structure of the load-bearing foot from collapsing. Engineers frequently use this type of ‘bow-string beam structure’ in the construction of bridges.

In his 1954 paper Hicks described the ‘windlass mechanism’. When the toes are dorsi-flexed at the MTP joints the related plantar aponeurosis processes are ‘wound around’ the MT head and the ‘bow-string’ is effectively shortened. The longitudinal bony structure then ‘bends’ at its inter-tarsal joint(s) and the resulting movement has usually been described as a ‘rising of the foot arch’.

The longitudinal ‘beam’ **must** alter its shape when the ‘bow-string’ effectively ‘shortens’, but the resulting intrinsic joint movements occur in **all three** planes. The mid-foot is elevated, but there are also lateral and medial swing movements, and rotations into supination and pronation (unlike any civil engineer’s bridge).

C. Plantar-flexion control of the toes

Some authorities have suggested that the small intrinsic muscles of the foot can control plantar-flexion of the toes against the ground, similar to the control of isolated flexion movement of the fingers at the MCP joints in the hand.

They are certainly capable of contributing to toe control. Patients with loss of arm and hand function can develop fine movement and 'hand-like' toe function. The small muscles may contribute to toe movement and activity when single foot balancing, but it is unlikely that they make significant mechanical contributions during normal walking and running.

The 'reversed windlass mechanism' of the plantar aponeurosis (slides 10–13)

In his 1955 paper Hicks described the **reversed windlass mechanism** of the plantar aponeurosis. When the plantigrade foot becomes load-bearing the longitudinal structure flattens and the distance between the heel and the MT heads increases. The plantar aponeurosis processes then tighten and this increased tension causes the corresponding toes to be pulled down into plantar-flexion at the MTPJs. The inter-phalangeal joints of the toes are stable in extension, and so the straight toes (held flat against the ground) can continue to act as strong support levers when heel elevation takes place. With heel elevation the accompanying activity of the 'windlass mechanism', as the proximal phalanges are moved into dorsiflexion at the MTPJs, maintains (increases) the plantar-flexion forces on the toes and the longitudinal foot structure also shortens – but with accompanying tri-planar movements at the intrinsic inter-tarsal joints.

Hicks thus showed that the longitudinal foot structure consists of 5 independent 'bow-string beams' based on the individual metatarsals, with the plantar aponeurosis processes acting as adjustable tie-bars. The plantar-flexion force of each toe against the ground is proportional to the tension in its aponeurotic process, and that in turn is directly related to the loading stress on the individual 'metatarsal bow-string beam structures'.

The work of John Hicks showed very clearly that **the reversed windlass mechanism is the main plantar-flexor mechanism for the toes at the MTPJs when the forefoot is load-bearing.** This has not always been accepted or fully appreciated. This may possibly be due to the publication of the 1955 Hicks paper in *Acta Anatomica* (not as widely read as the *Journal of Anatomy*). It is still infrequently cited.

D. Control of splay of the metatarsals across the forefoot (slides 14–16)

Previously it has been widely accepted that the lateral splay of the load-bearing metatarsals at forefoot level is controlled by adductor hallucis.

An alternate explanation – the importance of the deep transverse metatarsal ligaments and the plantar plates of the MTPJs as they form a transverse forefoot tie-bar

The forefoot 'transverse tie-bar'

In 1991 as a result of dissections of the forefoot carried out by Mrs Christine Harkness in Newcastle, and subsequent investigations, we have shown that the plantar plates of the MTPJs and the intervening deep transverse metatarsal ligaments form a very strong continuous structure across the plantar aspect of the forefoot. As each plantar plate is firmly attached to its metatarsal head by the collateral ligaments this strong transverse tie-bar is able to control splay across the full forefoot, and also splay between individual metatarsal rays when only part of the forefoot is load-bearing.

E. The forefoot ‘transverse tie-bar’ and the plantar aponeurosis form a ‘multi-segmental’ tie-bar system (slides 17–20)

Further dissections demonstrated that the longitudinal tie-bar of the plantar aponeurosis is inserted into the full width of the forefoot transverse tie-bar: i.e. into both plantar plates and deep transverse metatarsal ligaments. There is therefore a complete plantar tie-bar system capable of supporting the five longitudinal adjustable bow-string beam structures and controlling splay between the MT heads of the whole forefoot, or just the medial or the lateral rays when only part of the forefoot is taking load.

The functional control of the tie-bar system is automatic – responding to load-bearing strain to the individual bow-string beam structures through the metatarsal heads, and so provides a strong energy efficient mechanism.

This multi-segmental tie-bar system is one of the most important support mechanisms responsible for maintaining structural stability of the foot, and controls the basic toe posture plantar-flexed against the ground when the forefoot is load-bearing.

F. Structure of the plantar pad (slides 21–31)

The structure of the plantar pad was previously described by Bojsen-Møller and Flagstad (1976) and shown to be a multi-locular fat containing pad extending across the full width of the forefoot, and lying beneath the metatarsal heads and the proximal phalanges.

Further dissections and MRI scan investigations have been helpful in demonstrating more anatomical details and functional significance

The importance of the structure of the plantar aponeurosis, its relationship to plantar pad anatomy, and its load-bearing function

Our recent studies have shown that the plantar aponeurosis is composed of two layers – a superficial layer and the strong deeper aponeurotic ‘tendinous’ layer. In the proximal part of the foot the two layers are joined together but beneath the metatarsal shafts they separate in between the definitive 5 individual deep processes to form the four fat bodies. At the level of the metatarsal necks the deep processes separate from the superficial layer, and each process then divides into two extensions that pass around the flexor tendons to be inserted into the MTPJ plantar plates and the DTMLs. With the separation of the ‘strips’ of the superficial layer from the ‘aponeurotic processes’ the fat bodies on either side become continuous with each other and the plantar pad is then formed. The pad thus extends across the full width of the forefoot at metatarsal head level, and also extends forwards beneath the proximal phalanges of the toes as far as the level of their necks. NB: the pad is formed between the two layers of the plantar aponeurosis and is continuous with the fat bodies.

Proximally the plantar pad lies beneath the MTPJ plantar plates (with the respective flexor tendon sheaths) and the intervening deep transverse metatarsal ligaments. More distally, the dorsal margin of the plantar pad is limited by the shafts of the proximal phalanges and the mooring ligaments that extend between flexor tendon sheaths of the lateral four toes.

Due to the action of the reversed windlass mechanism the proximal phalanges and intervening mooring ligaments have the capability of compressing the distal part of the plantar pad, and so share appropriate load distribution with the area beneath the MT heads for each of the load-bearing metatarsal rays.

The plantar pad/reversed windlass mechanisms also allow the skin beneath the plantar pad to be ‘laid out on the ground’ at the time of forefoot contact when walking and running, skin scuffing is therefore minimal, and the plantar skin and pad can remain ‘stationary’ on the ground surface when overlying foot movements take place and heel elevation occurs (**slide 31**).

G. The plantar aponeurosis and gastrocnemius form a ‘two part’ propulsive mechanism (slide 32)

In comparative studies of the leg musculature of hum[illegible]422(d)1.442422(t)0.76259(T)-3.(h)1.48.003]TJ conversely the mid-foot has the ability to ‘twist’ relative to a stationary (plantigrade) forefoot.

(v) Huson has pointed out that since the end of the 19th Century it has been realised that the movements at the talo-calcaneal, calcaneo-cuboid and talo-calcaneo-navicular joints are always linked and coordinated. Individual joint movement cannot take place independent of the other joints. He has explained the concepts of ‘**open chain’** and ‘**closed-chain’** movements in relation to the human foot (**see slides 36–37**).

(vi) De Doncker and Kowalski (1970) recognised that the second and third metatarsals had little independent lateral movement and so formed a stable central segment in the forefoot (**slide 38**).
fo o

I. Evidence for a Stable Central Forefoot Segment and Development of the Concept of the Foot as a ‘Four-part Mechanism (slides 39–42)

Our investigations in Newcastle have confirmed the lateral stability of the 2nd and 3rd metatarsals in relation to the middle and lateral cuneiform bones (as described by Kowalski and De Doncker), but in addition our studies suggest that the navicular and cuboid must be included in an extended central forefoot segment.

The first MT ray, and the 4th and 5th provided appropriate support and mobility for Hicks forefoot twist mechanism and provide an adaptive mechanism when standing on sloping ground – but the forefoot ‘twist’ also functions when mid-foot pronation and supination movements take place beoe a (plantigrade and proximally (talar dome reasonably horizontal), to allow plantigrade foot contact with the ground and maintain an upright posture during activity, and to cope with uneven surfaces. Nevertheless the studies of Hicks 1953, Van Langelaan 1983, Benink 1985, Lundberg et al 1989, and Winson et al 1994, provide detailed information of the patterns of movement at the intrinsic joints and coordinated motion within the overall foot structure during functional activity.

Lewis (1989) made the observation that the human foot is unique in having lateral swing movement at transverse tarsal joint level. Recognising this obvious fact has changed my understanding as to why the coordinated movements at the inter-tarsal joints have developed and the important purpose they serve.

Careful observation of the foot when single foot balancing (with indicator sticks attached at mid-foot and lower tibial level), and then during the 'great toe extension test' (GTET), have shown that accompanying the lateral and medial swing movements at the transverse tarsal joints, the mid-foot consistently undergoes marked supination and pronation movement. If the forefoot is to remain plantigrade on the ground – and the leg remain reasonably vertical to maintain an upright posture – there is then an obvious necessity for simultaneous compensatory (and opposite) pronation or supination motions to occur in both the forefoot and hindfoot. These coordinated movements are a clear illustration of Huson's **'closed chain' linkage**.

The Hicks **'forefoot twist'** mechanism (**slides 34–35**) explains the necessary compensatory forefoot movements, but understanding the coordinated movements in the hind-foot has remained a challenge. Nevertheless, the simple GTET demonstrated that the pronation/supination movements of the calcaneus were always less than those of the mid-foot (navicular and cuboid).

K. Coordinated Movements at the Inter-tarsal Joints of the Mid-foot and Hind-foot (slides 46–65)

The coordinated movements at the 'four joints' of the mid-foot and hind-foot were studied by Ambagtsheer (1978). Illustrated at **slides 46–49**.

He investigated the tri-planar rotatory movements of the individual bones by inserting pins into each bone and placing the foot in an apparatus that allowed photographs to be taken in all three planes. The tibia was rotated over the 'stationary' foot and photographs taken to record the resulting tri-planar movement of each pin.

He was able to demonstrate that with external rotation of the tibia there was outward angulation at the transverse tarsal joint and the navicular and cuboid became supinated, and they and the metatarsals moved into relative internal rotation and plantar-flexion (that is **relative** to the talus and calcaneus).

Thus, **with outward swing angulation** at the transverse tarsal joint (from an inwardly angulated position) the coordinated movements of **the forefoot segment** (**navicular and cuboid**, **lateral and central cuneiforms and 2nd and 3rd metatarsals**) are:

Supination
Internal Rotation
Plantar-**f**lexion

The movements of **calcaneus** relative to the supinated **cuboid** (and **navicular**) are therefore the opposite:

Pronation (but relative to the ground it **supinated** half as much as the **cuboid**)

External Rotation
Dorsiflexion

The movements of the **talus** relative to the supinated **navicular** (and cuboid) **and the calcaneus** are:

Pronation (but no actual rotation in relation to the ground in the coronal plane and so the horizontal position of the talar dome was maintained, while the calcaneus and navicular underwent supination beneath the talus)
External rotation (external rotation of talus relative to navicular is twice as far as to calcaneus)
Dorsiflexion (relative to the ground talus dorsiflexes twice as much as calcaneus)

These coordinated patterns of movement are inevitable when the forefoot remains plantigrade and tibia 'vertical' and the mid-foot angulates outwards (an example of closed chain motion).

Thus, when the mid-foot (navicular and cuboid) **SUPINATES** the **distal bones** at each of the three mid-foot/hind-foot joints (calcaneo-cuboid, talo-calcaneal and talo-calcaneo-navicular) undergo the following tri-planar motions relative to the proximal bone:

Supination
Internal Rotation **S I P-f**
Plantar-**f**lexion

It follows that the relative tri-planar movements of the proximal bones relative to the distal joint surface are then:

Pronation
External Rotationn **P E D**
Dorsiflexion

When **inward angulation** occurs at the transverse tarsal joints and the mid-foot undergoes **pronation**, the relative tri-planar movements are reversed:

The distal bones undergo relative

Pronation
External Rotation **P E D**
Dorsiflexion

And the proximal bones undergo relative:

Supination
Internal Rotation **S I P-f**
Plantar-**f**lexion

I have found it helpful to remember **PED** and **SIP-f** and apply these tri-planar movement combinations when trying to understand mid-foot and hind-foot coordinated movements

L. Diagrams illustrating the three-dimensional movements at the Inter-Tarsal Joints: Forefoot and Hind-foot (slides 50–63)

These have been produced following cine-radiographic, clinical, and osteological studies investigating the coordinated tri-planar foot movements. They attempt to show the sequence of movements with the great toe extension test giving outward angulation at the transverse tarsal joint.

I am now convinced that the shape of the joint surfaces and the position and ‘tightness’ of the controlling ligaments of the C-C, T-C and TCN joints make the resulting coordinated movements inevitable (as suggested by Professor Huson).

M. Precis of the Ambagtsheer results (slides 64–65)

These provide similar patterns of movement as given in the slides for **K** and the recorded rotation movements. With outward angulation at the transverse tarsal joint and supination of the mid-foot the cuboid supinates twice as far as the calcaneus, and the talus externally rotates twice as far as the calcaneus.

N. Diagrams illustrating the mid-foot outward rotation and angulation and the compensatory rotations in hind-foot and forefoot (slides 66–69)

These demonstrate the lateral swing movements at the transverse tarsal joints. The decreased density of the green/pink (supination/pronation) colouring for the calcaneus in slides 56 to 58 indicates that the calcaneus has supinated/pronated half as much as the central stable forefoot segment. It should also be clear that as these swing movements take place the talus externally/internally rotates twice as much as the calcaneus.

O. The foot skeleton in postures of ‘neutrality’, lateral and medial swing angulation at transverse tarsal joints with the corresponding compensatory (‘closed-chain’) forefoot and hind-foot rotations demonstrated (slides 70–74)

P. A Hypothesis: an explanation for the lateral and medial swing movements at the mid-foot, the mid-foot supination and pronation rotations, and compensatory adjustments in forefoot and hind-foot (slides 75–76)

In the various postures between full internal angulation and mid-foot pronation, and full outward angulation and mid-foot supination, the three main forces acting on the foot in the sagittal plane, i.e. the support at the hind-foot (tendo Achillis and/or plantar pressure under heel), the centre of body gravity mass line through the talus, and the centre of forefoot/mid-foot pressure, can be kept in line. The foot is then able to act as a **balanced lever**.

The ‘balanced’ foot, supported by three layers of plantar ligaments (capsular, long plantar and the aponeurosis) can be stable when under static or dynamic stress/strain in all ‘balanced postures’.

Q: The lateral 'swing' movements at the mid-foot level provide a mechanism for lateral balance (slides 77–79)

As the medial/lateral swing movements occur at transverse tarsal joint level the ankle also moves from side to side. Controlling this provides a mechanism for lateral balance (like a juggler balancing a vertical pole).

It is suggested that the lateral swing movements at the transverse tarsal joints, and therefore the lateral balance mechanism, are controlled by tibialis posterior and the peronei and their related 'stretch reflexes'.

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References

1. Ambagtsheer JBT. The function of the muscles of the lower leg in relation to movements of the tarsus. An experimental study in human subjects. *Acta Orthop Scand* 1978; Suppl 172. Copenhagen, Munksgaard.

2. Bojsen-Møller F, Flagstad KE. Plantar aponeurosis and internal architecture of the ball of the foot.J Anat 1976; 121(3): 599.

3. De Doncker E, Kowalski C. Le pied normal et pathologique. *Acta Orthopaedica Belgica* 1970. Tome 36; Fasc 4-5: 386-559.

4. Elftman H. The transverse tarsal joint and its control. *Clin Orthop* 1960; **16**: 41.

5. Hicks JH. The mechanics of the foot. I: The joints. *J Anat* 1953; **87**: 345 – 357.

6. Hicks JH. The mechanics of the foot. II: The plantar aponeurosis and the arch. *J Anat* 1954; **88**: 25 – 30.

7. Hicks JH. The foot as a support. *Acta Anat* 1955; **25**: 34 – 45.

8. Hicks JH. The mechanics of the foot IV. The action of muscles on the foot in standing 1956. *Acta anat*; 27: 180-192.

9. Hicks JH. The three weight-bearing mechanisms of the foot. 1961; In *Biomechaniscal Studies of the Musculo-skeletal System* (Ed FG Evans). Springfield, IL., Charles C Thomas.

10. Huson A. “Een Ontleed kundig Functioneel Onderzoek van de Voetwortel” (A functional and anatomical study of the tarsus). Ph D Dissertation, Leiden. Leiden University, 1961.

11. Huson A. Joints and Movements of the Foot: Terminology and Concepts. *Acta Morphol Neerl-Scand* 1987; **25**: 117-130.

12. Huson A. Functional Anatomy of the Foot. In *Disorders of the Foot and Ankle* (Ed M H Jahss) 1991, 409-431. Philadelphia, W B Saunders Company.

13. Lewis OJ. The joints of the evolving foot. Part II. The intrinsic joints. *J Anat* 1980; **131**: 275-57.

14. Lewis OJ. *Functional Morphology of the Hand and Foot* 1989; 253. Oxford, Clarendon Press.

15. Lundberg A, Svensson, OK, Bylund C, Goldie I., Selvik G. Kinematics of the ankle/foot complex. Part 2: Pronation and supination. *Foot Ankle* 1989; **9** (5): 248-253.

16. Lundberg A, Svensson, OK, Bylund C, Selvik G. Kinematics of the ankle/foot complex.Part 3: Influence of leg rotation. *Foot Ankle* 1989; **9** (6): 304-309.

17. MacConaill MA. The postural mechanism of the human foot. *Proc R Ir Acad* 1945; **50**(14): 265.

18. MacConaill MA, Basmajian, JV. Muscles and Movements: *A Basis for Human Kinesiology* 1969; 74–84. Baltimore, Williams and Wilkins.

19. Manter JT. Movements of the subtalar and transverse tarsal joints. *Anat Rec* 1941; **80**: 402.

20. Stainsby GD. Pathological anatomy and dynamic effect of the displaced plantar plate and the importance of the integrity of the plantar plate–deep transverse metatarsal ligament tie-bar. *Ann R Coll Surg Engl* 1997; **79**: 58-68.

21. Van Langelaan EJ. A kinematical analysis of the tarsal joints. An X-ray photogrammetric study, 1983. *Acta Orthop Scand*; 54 (Suppl 204). Copenhagen, Munksgaard.

22. Winson IG, Lundberg A, Bylund C. The pattern of motion of the longitudinal arch of the foot. *The Foot* 1994; **4**: 151 – 154.