Question: You trained as a general orthopaedic and trauma surgeon and became a Consultant in Newcastle in 1968.

How did you become so interested in conditions of the foot?

As an Orthopaedic trainee in Sheffield and Oswestry I was taught the then accepted procedures for common foot conditions. It was mainly basic salvage surgery as there was little understanding of the normal functional anatomy apart from the windlass mechanisms of the plantar aponeurosis that John Hicks had described.

Then, as a new consultant I was referred patients from the Rheumatology Clinic, many of whom had severe forefoot deformities, such as hallux valgus, severe clawing of the lesser toes, and marked prominence of the metatarsal heads in the sole of the foot that were very painful when weight-bearing.

I had been taught to treat such severe Rheumatoid deformities by excision of the metatarsal heads.

One day whilst doing such a forefoot excision arthroplasty I found that when the metatarso-phalangeal joints were exposed their plantar plates had moved onto the dorsal aspect of the metatarsal heads as well as the bases of the proximal phalanges, and the depression of the metatarsal heads did not correct until they were returned to their correct position.

Wishing to know more about the pathological anatomy of these deforities I asked the University Anatomy School for their help

Mrs Christine Harkness, a skilled technician in the University School of Anatomy first dissected a normal forefoot and showed the plantar plate and deep transverse metatarsal ligament anatomy. This for me was life-changing as it completely altered my appreciation of how the human forefoot is stabilised and functions, and it stimulated a lasting curiosity and interest in foot mechanics.

These dissections of the normal foot showed that the forefoot is held together by a very strong and continuous transverse tie-bar made up of the plantar plates of the metatarso-phalangeal joints of the toes, each attached to the metatarsal head by its capsular collateral ligaments, with the thick and strong deep transverse metatarsal ligaments between them. It was clear that this continuous structure of alternate plantar plates and deep transverse metatarsal ligaments controls lateral splay between neighbouring metatarsal heads when the forefoot is load-bearing, and it tightened when the first and fifth metatarsal heads were pulled apart.

We also found that the 5 deep processes of the plantar aponeurosis were inserted into the full width of this transverse tie-bar and the bases of the proximal phalanges, and we were able to confirm John Hicks's observations relating to the windlass mechanisms of the aponeurosis.

As long ago as 1954, in the *Journal of Anatomy*, Hicks described the windlass mechanism of the plantar aponeurosis with dorsiflexion of the great toe causing elevation of the arch of the foot. The next year, in *Acta Anatomica,* he described the plantar aponeurosis as acting as a longitudinal tie-bar beneath each of the five metatarsal rays, and suggested that the human foot had a 5-part longitudinal bow-string beam structure, rather than an ‘arch’. With weight-bearing the load-bearing metatarsal rays flatten and lengthen and so tighten their related aponeurosis processes that the toes are pulled down into plantar-flexion and lie flat against the ground. Unfortunately, the importance of this second paper was not always recognised and it is rarely cited.

Our dissections showed that as the five longitudinal deep processes of the plantar aponeurosis cross over the transverse forefoot tie-bar they become integrated with the plantar plates of the metatarso-phalangeal joints. When the metatarsal heads are submitted to upward pressure to simulate weight-bearing, the toes become plantar flexed at the metatarso-phalangeal joints by the reversed windlass mechanism as the plantar aponeurosis processes supporting the stressed metatarsal rays tighten, but forefoot splay also occurs with the metatarsal heads moving apart, and then the intervening deep transverse metatarsal ligaments became tight.

We therefore concluded that the human foot skeleton rests on and is supported and controlled by a multi-segmental ligamentous transverse and longitudinal tie-bar system. This provides the basic support mechanisms for control of the splay of the forefoot, as well as maintaining stability of the longitudinal metatarsal bow-string beam structures of the normal foot when it bears weight. Muscle activity is then available to actively alter foot posture and control balance, as well as provide propulsive forces.

Question: So that helped your understanding of the normal foot structure and function, and the importance of the multi-segmental tie-bar system. Were you able to find out what happened when foot deformities developed.

Yes. We dissected feet with typical forefoot abnormalities and found that deformities of the toes, and abnormal flattening – even collapse – of the longitudinal bow-string beam structure of the foot, happen when there is a breakdown in the multi-segmental tie-bar system.

When we dissected a foot with typical severe rheumatoid forefoot deformities we found that the Hallux valgus deformity developed when the medial capsule of the first metatarso-phalangeal joint became stretched, and the metatarsal head then moved medially over its sesamoids. The great toe was then pulled into valgus by its windlass mechanisms as their line of pull was now lateral to the metatarso-phalangeal joint. The varus deformity of the little toe was the result of the *giving way*, of the lateral end of the transverse tie-bar system and the 5th metatarsal head then moving outwards.

When we looked at the pathology of the rheumatoid lesser toe deformity, the dissections showed that the proximal part of the plantar capsule of the metatarso-phalangeal joints had become stretched over the prominent metatarsal head and sometimes even ruptured in the thinner grooved area for the flexor tendons. The more distal part of the plantar plate and the base of the proximal phalanx had moved distally around the metatarsal head onto its dorsal aspect, with the toe becoming clawed. The extensions from the deep process of the plantar aponeurosis were found to have slipped dorsally on each side of the metatarsal neck and through their attachment to the dorsally displaced plantar plate and phalangeal base were then causing active depression of the metatarsal head. The toe deformity and metatarsal head depression were only corrected after the base of the proximal phalanx was removed and the plantar plate returned to its normal plantar position.

In 1993 the results of our early findings that a multi-segmental tie-bar system provides the basic support and control mechanisms for the foot as a 5-part bow-string beam structure, that the normal postural control of the toes of the load-bearing metatarsal rays is essentially by the windlass mechanisms as described by Hicks, together with our understanding of the pathological changes in the tie-bar system underlying the commonly seen toe deformities of Hallux valgus and clawing of the lesser toes, were presented in a Royal College of Surgeons Lecture

Question: And presumably these findings altered your approach to the management of foot deformities?

Indeed. When I began to understand the pathological anatomy and the resulting abnormal forces in the severely deformed rheumatoid forefoot, an alternative operation was designed with the idea of preserving the metatarsal heads. This was introduced as following some of my early metatarsal head excision procedures a number of patients continued to have forefoot pain.

In this new procedure the base and most of the shaft of the proximal phalanx of each clawed lesser toe were removed to release the claw deformity, the dorsally displaced plantar plates of the metatarso-phalangeal joints were returned to their correct position below the preserved metatarsal heads, and the plantar pad followed. The toes were temporarily stabilised with K wires. A Keller's type procedure was carried out to the great toe. Although the windlass mechanisms of all the toes were therefore de-functioned, the length of the metatarsal rays was preserved and the metatarsal heads were covered by their normal plantar pad tissues and able to take some weight. Most patients were much improved, nevertheless it was still a salvage procedure.

The results in 69 feet in 52 patients were independently reviewed by Mr Peter Briggs, a Newcastle Consultant Orthopaedic Surgeon, and published in 2001.

For the correction of deformities in the non-rheumatoid foot, the main aim of surgical treatment was, as far as possible, to restore the integrity and normal function of the multi-segmental tie-bar system and the toes, and preserve normal movements at the intrinsic joints of the foot.

Question: The concept of the foot skeleton having a longitudinal and transverse tie-bar system supporting and controlling its bow-string beam construction, and the splay of the forefoot, is now generally accepted. But you have also stressed the importance of Professor Lewis's observation that the human foot has a unique lateral swing movement at the transverse tarsal joint level.

Yes, and another chance event stimulated my interest in this concept.

In the mid - 1990's I came across Professor O J Lewis's remarkable book entitled 'Functional Morphology of the Evolving Hand and Foot', published in 1989. Within his extensive research into the evolution of tetrapod limb structure and activity, he studied the gradual development and alterations in the skeletal patterns and musculature of the lower leg, in Reptiles, Mammals, and Primates …. and then Man.

He drew attention to the evolving changes to the Plantaris muscle and the site of insertion of its tendon with the progressive evolution of reptilian and mammalian foot structure, and finally in the human plantigrade foot in relation to the changes in the distal insertion of the Plantaris tendon. In reptiles and birds the tendon is inserted into the base of the proximal phalanx and their toes lie flat on the ground, in dogs and cate it is into the middle phalanx and toes are slightly flexed, in hoofed animals the tendon insertion is to the distal phalanx,. He then desribed the realignment of the human forefoot, with the evolution of the hallux from the ape-like adducted position to become orientated longitudinally to lie beside the 2nd toe, and the significance of the adaptation of the Plantaris tendon as the plantar aponeurosis. In the human foot the tendon of Plantaris has become attached to the calcaneus and distally is inserted into the base of the proximal phalanges. It is the main adaptation that gives our foot a bow-string beam structure and the windlass mechanisms that control the toes. When the aponeurosis tightened the toes therefore become plantar-flexed and flat on the ground flat as seen in the reptiles and birds, but is the

But for me Professor Lewis's most significant and revealing observation, was that in sub-human Primates the movement of the cuboid relative to the calcaneus is mainly a rotation about a longitudinal axis, whereas (and I quote) 'in Man this rotatory movement is much reduced and instead a unique medial and lateral swing motion had developed at the transverse tarsal joint'. He also stressed the importance of the stability of the human calcaneo-cuboid joint and noted that 'with the outward swing movement the mid-foot supinated, and the cuboid beak was then impacted into its slot on the calcaneus under the sustentaculum tali.'

This description of a mid-foot lateral swing as well as rotatory movement could provide an explanation for the weight-bearing foot of Man being able to twist into supination or pronation at the transverse tarsal joint level while the forefoot and ankle joint remained horizontal in the coronal plane.

The necessary compensatory rotation required for the forefoot could be explained by the metatarsal twist mechanism previously described by Hicks, but the pattern of coordinated movements in the hind-foot and how the foot remains stable as the mid-foot rotatory movements occurred has not been previously explained.

Following further anatomical and radiological studies, in particular modern CT and 3-dimensional MRI investigations to show the coordinated movements at the sub-talar and transverse tarsal joints, an explanation can be suggested. The ligaments controlling the calcaneo-cuboid joint and talo-calcaneal joints were found to stay tight throughout their range of movement, and a talar slide mechanism was demonstrated that enabled the ligaments around the talo-calcaneo-navicular joint to also tighten when the foot was weight-bearing. So with the support of the plantar aponeurosis and its windlass mechanisms and the ligaments of the mid-tarsal and sub-talar joints able to remain tight as foot posture alters, the ability of the weight-bearing foot to remain stable as lateral mid-foot swing and rotational movements occur, while the forefoot and talar dome remain horizontal in the coronal plane can be explained.

We have concluded that the 2^{nd} and 3^{rd} metatarsal rays, the middle and lateral cuneiforms, the navicular and cuboid, together with the talus and calcaneus, form the main central longitudinal bow-string beam structure stabilised and controlled by the plantar ligaments and the aponeurosis. Anteriorly this central beam receives medial and lateral support from the 1^{st} and the 4^{th} and 5^{th} metatarsals, as previously suggested by de Doncker and Kowalski, with the metatarsal heads held together by the transverse tie-bar.

When the mid-foot is pronated and inwardly angulated the central beam and 1^{st} metatarsal ray are the predominant load-bearing sections, and when it is supinated and outwardly angulated the central beam receives lateral support from the 4^{th} and 5^{th} metatarsal rays.

The tendons of Tibialis posterior and the Peronei, are clearly ideally placed to control and adjust the lateral swing movements at the transverse tarsal joint level that are necessary for lateral balance.

The windlass mechanism of the great toe automatically supinates the mid-foot as heel elevation takes place when walking and running, and this change in foot posture and alignment, with the accompanying lateral movements of the mid-foot and ankle, are able to alter the projection of ground reaction forces so that they propel the centre of body mass over towards the other foot when it contacts the ground at the next step.

The human foot is a remarkable mechanism, and a finely engineered structure, and is undoubtedly one of the main attributes that allow Man to be the dominant quadruped on Planet Earth today.

Question: Unfortunately, it would seem that this remarkable mechanism is still liable to failure as many people develop deformities that limit their activities. Is the outlook improving?

I have particular concerns that many of these foot deformities and structural failures are related to the wearing of inappropriate contemporary footwear. Most shoes that are worn, particularly by women, are not wide enough for the forefoot to splay when it is weight-bearing, and they often have pointed or curved toe boxes that push the great toe laterally. The unique windlass mechanisms of the great toe, so important for foot support and control, are progressively weakened as the great toe becomes angled outwards and its windlass mechanisms gradually lost. When there is marked hallux valgus the inner side of the longitudinal foot structure loses its main bow-string beam support from the first metatarsal ray and it flattens. The foot structure can then gradually fall apart.

Some 15 years ago we did a study of young people’s feet in 3 Northumberland schools. First I visited a respected shoe shop and the available shoes suggested for school age children were kindly shown to me. The outline of all the shoes was drawn and valgus angle of the inner toe margin measured. It was found that as the size of the shoes increased for the age range of 5 to 18, so did the outward angulation of the inner side of the toe box, and this was found to be greater in shoes made for girls (increasing to 18 degrees) than for boys (consistently 2 to 4 degrees less). In a group of over a hundred schoolgirls aged 15 to 18, 25% of them had a great toe valgus angulation of between 10 to 15 degrees, in 10% it was between 15 and 20 degrees and in 5% more than 20 degrees. Only 5% of boys in this age range had a slight great toe valgus angulation of 10 to 15 degrees. It was our understanding that many girls began to wear fashion shoes as early as age 12.

Of 60 women attending orthopaedic clinics for non-foot-related conditions, 40% had between 20 and 30 degrees of valgus angulation of the great toe, and in a further 30% it was more than 30 degrees. All were wearing pointed toed shoes that were narrower than their weight-bearing forefeet.

It is generally accepted that shoes must have adequate length, but it is not always appreciated that they must have also have sufficient width to accommodate the forefoot and toes when they are weight-bearing. Most importantly shoes need to have a straight inside border all the way down to the end of the toe cap. This is particularly important when buying shoes for children. Even the rounded toe box shape can push the great toe into valgus.

High heeled shoes with pointed toes will inevitably produce severe toe deformities. Not only does the foot slide down a slope and become wedged in the toe-box but greater weight is taken on the forefoot in the heel elevated posture.

I have no doubt that most common toe deformities are preventable. But, women in particular are daily exposed to pressure from advertising and role models which will damage their feet.

Orthopaedic Surgeons must take on their responsibility to educate the public and persuade the fashion industry to market and promote ‘foot-shaped shoes’.