Introduction

The chronic hyperglycemia of diabetes, a highly widespread chronic disease, is associated with long-term damage, dysfunction, and failure of various organs. In particular, patients experience neuropathy and blood vessels degeneration. These two complications develop into the foot disease which alters the biomechanics of gait and eventually leads to the formation of callosity and ulcerations ***(Sawacha et al., 2009)***.

Foot complications occur in both forms of diabetes and are related more to the period of time that the illness has been present than to the age of onset ***(Reiber et al., 1995)***.

The remarkable pathogenesis of the diabetic foot is neuropathy, macrovascular and microvascular disease. These processes may occur exclusively or they may occur together in varying degrees, placing the patient at risk of morbidity, such as ulceration, gangrene and infection. This is especially true if these pathologic changes are combined with foot deformity, making the patient more vulnerable to foot problems ***(Murray and Boulton, 1995).***

Foot deformities resulting from neuropathy, abnormal biomechanics, congenital disorders, or prior surgical intervention may result in high focal foot pressures ***(Reiber, 1999; Frykberg RG, 1998; Mayfield, 1998; Schoenhaus,***

1991; Frykberg RG, 1995; Veves, 1992). This may lead to vulnerable areas on the foot predisposing to ulcerations. These areas are primarily located plantarly, although medial and dorsal ulcerations may occur from footwear irritation. Such deformities might include prior partial foot amputations, prominent metatarsal heads, hammertoes, Charcot arthropathy, or hallux valgus.

Diabetes continues to be the most common underlying cause of lower extremity amputation (LEA) ***(American Diabetes Association 2000; Centers for Disease Control 2000; U.S. Department of Health and Human Services 1997, American Diabetes Association 1996, Reiber et al., 1995; Frykberg RG, 1999).*** Generally, the rate of LEA in the diabetic population is 15-40 times higher than that found in non diabetic individuals, with males having rates at least 50% greater than diabetic women ***(American Diabetes Association 2000; Frykberg RG 1999; Harris MI, 1998).*** When risks for LEA are compared between diabetic and non diabetic populations worldwide, it becomes clearly apparent that both diabetes and ethnicity have profound implications on rates of lower limb amputation ***(Frykberg RG, et al., 1998).***

Survival rates after diabetes-related lower extremity amputation are significantly lower than those in age-matched non diabetic individuals as well as in persons with diabetes without history of amputation ***(Reiber et al., 1995; Frykberg et***

al., 1998; Larsson et al., 1998). The 3-year and 5-year survival rates are about 50% and 40%, respectively, with the major cause of death being cardiovascular disease ***(American Diabetes Association, 1996).***

Diabetes has a huge impact on personal and nationwide economics. The individual cost to receive adequate general care for diabetes has increased dramatically in that past 2 decades. The cost of diabetic medication and the intensity of treatment for heart disease, renal failure, and the like have reached shocking proportions. It is worth noting here that as frequent and expensive as treatment of diabetic renal disease is, the cost for the management of diabetic foot complications exceeds all of the costs for renal dialysis for all diabetic patients. The cost of treating foot complications is largely preventable ***(Wieman et al., 1998).***

The social and economic burden of the diabetic foot can be reduced through early diagnosis and treatment ***(Fedele et al., 1997).***

In rehabilitating a diabetic foot patient we should consider that every individual is unique. A rehabilitation program should be tailored according to their needs and we suggest that it should be directed to the biomechanical alterations and vascular and neurophysiological dysfunction. This is followed by the shoe prescription, fabrication and fitting.

Aim of the Work

This work aims at elucidation of the recent advances in assessment of the biomechanical alteration in relation to vascular and neurophysiological changes in diabetic foot in order to establish a protocol for rehabilitation that can prevent complications.

Chapter (I): 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) ***(Abboud, 2002).***

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 ***(Abboud, 2002):***

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 ***(Donatelli, 1990).*** 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 (*Abboud, 2002)*

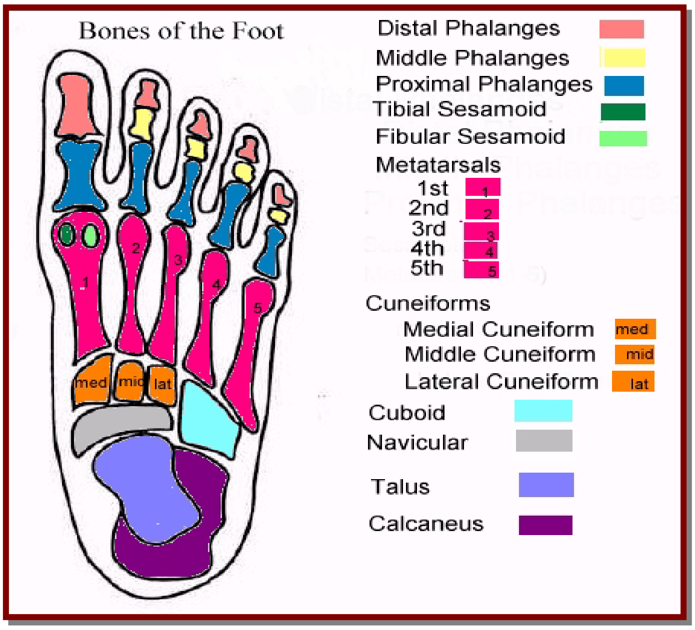

Fig. (1): The 26 bones (seven tarsals, five metatarsals, and 14 phalanges) and six joints (ankle, subtalar, midtarsal, tarsometatarsal, metatarsophalangeal (MTP) and interphalangeal (IP) joints) of the foot make up its four segments: the hindfoot, the midfoot, the forefoot and the phalanges.

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 plantar flexion 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 sites 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 ***(Manter, 1946).***

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 ***(Abboud, 2002).***

Foot Function *(Abboud, 2002)*

Joints of the foot are controlled by extrinsic and intrinsic muscles of the lower limb to allow 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.

The foot is defined as being plantar flexed 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.

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.

The foot is considered to be supinated when it is simultaneously adducted, inverted and plantar flexed, and pronated when it is abducted, everted and dorsiflexed.

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.

The minimum range of ankle joint motion as necessary for normal locomotion is 10º of dorsiflexion and 20º of plantarflexion. The ankle joint also has slight movement in the Tp during plantarflexion, causing instability of the joint in this position ***(Root, 1971).***

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 º from the Tp and 16 º from the Sp and resultant motion in Fp ***(Root,1971)***; 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 calcaneo-cuboid 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 90º 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 *(Abboud, 2002)*

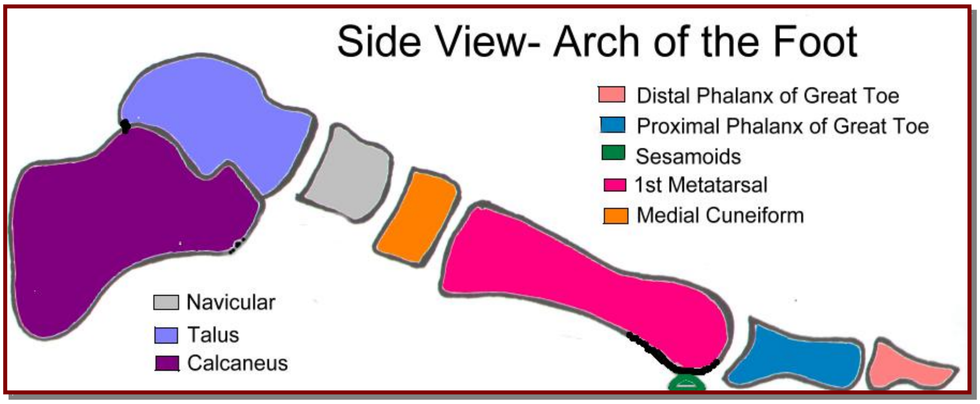

Fig. (2): The foot has to both support body weight whilst standing and to act as a lever to propel the body during locomotion. It must be able to conform to even and uneven surfaces, and thus be capable of making good contact with almost any supporting surface, forming a rigid platform that will not 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 *(Abboud, 2002)*

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 *(Abboud, 2002)*

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 in shoe sensors providing a direct description/orientation of foot posture.

Gait Analysis *(Abboud, 2002)*

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) *(Abboud, 2002)*

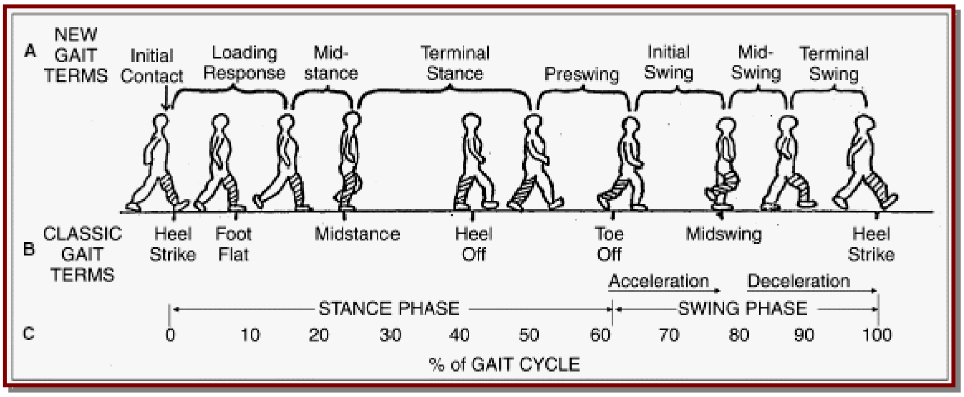

Fig. (3): During normal walking, one full GC is referred to as the time interval between two consecutive heel strikes of the same foot on the ground. This time interval is known as the stride time.

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,