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THE ROMANIAN ACADEMY

MEDICINE
Review *article*

FOOT FUNCTIONING PARADIGMS

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Received January 20, 2012

Foot pathomechanics conservative treatment prescription by indication of technical characteristics of medical devices used is based on a thorough understanding of normal and pathological functioning of lower limbs. Given the complexity of the osteoarticular and muscular system of the foot, the study of gait biomechanics is based on foot functioning paradigms by means of which correlations are established between the structure and the function of anatomical segments considered. The development of biomechanical models started from clinical observation, continuing with the complex kinematic and kinetic analysis using multi-segment foot models and integrating muscle activity monitoring. A reference point is the subtalar joint neutral paradigm, elaborated by Merton Root, DPM as unified system of defining normal and pathological foot. The evolution of biomechanical assessment techniques has led to challenging the theoretical grounds of this paradigm, determining the emergence of new ones such as: tissue stress theory, sagittal plane facilitation or neuromechanical/preferred motion pathway. High internal stress is one of the causes of diabetic foot ulcers. Understanding the causes of this stress in the foot structure, based on these paradigms, is a prerequisite for successful conservative treatment of diabetic foot. This paper aims to briefly outline the most representative foot functioning paradigms.

Key words: diabetic foot, paradigm, conservative treatment.

INTRODUCTION

Recent research on diabetic foot ulcer prevention has revealed that failure of accommodative conservative treatment, registered in an important number of cases, can be explained by insignificant change (2%) of peak internal stresses in the structure of tissues corresponding to risk areas, despite significant changes (66%) in pressure at the foot-supporting surface contact area interface[1].

This paper aims to briefly outline the main foot functioning paradigms presented in medical literature, paradigms without which a documented prescription of a functional conservative treatment for diabetic foot cannot be made. Normal and pathologic functioning of the foot and lower limbs is of important concern for medical professions such as orthopedics, medical rehabilitation, physiotherapy or podiatry, the latter still absent in Romania. The multitude of areas of activity involved in foot pathomechanics treatment has resulted in the emergence and development of several theories on lower limb biomechanics. An important application of these theories is the prescription of medical devices used in non-invasive conservative treatment of foot pathomechanics.

The Neutral Position of the Subtalar Joint. The development of podiatric biomechanics has gained momentum through the publication of papers focusing on normal and pathological functioning of the foot by Merton Root, DPM, *et al.* in 1971–1978 in the USA[4,5]. Root's great merit was creating a unified reference system based on normal foot definition by means of a set of 8 criteria of normalacy. This system takes into account the three-dimensional structure of the musculoskeletal system of the foot with the objective of predicting dynamic behaviour during the gait cycle. Developing a system for classification of structural anomalies in relation to this reference system was a logical product of this process. For a detailed understanding of foot biomechanics, Root suggests that a thorough knowledge of the relationship between the morphology and the function of this anatomical part is required. In constructing this paradigm, Root was influenced by the results of scientific research done by leading figures of that time, such as Inman, Elftman, Hicks or Wright. These researches aimed to identify the position of axes of motion of foot joints, with a particular interest in the subtalar joint, describing functioning mechanisms of various anatomical structures, assessing muscle activity and dynamic behaviour of the foot during the gait cycle. Based on personal clinical experience and results of research papers published at the time, Root introduced, as a reference of his system of classification of normal and pathological foot structure, the concept of neutral position of the subtalar joint, defined as the position in which the foot is neither in pronation, nor in supination. Based on clinical observation, it was established that, compared to the neutral position, there is a 2:1 ratio between the inversion and eversion movements of the rearfoot. Structural foot deformities can be identified and measured based on clinical examination, allowing to compare assessments of various clinicians due to this unique defining system. In the presence of a structural deformity or a muscle imbalance, during the gait cycle, the body is forced to resort to compensatory movements. These are changes in the structure, function and position of a body part as a response to deviations in the structure, function and position of another body part. Compensatory movements occur if temporary or permanent changes in the structure or function of lower limbs prevent efficient gait[2,4,5].

Criteria of normalacy issued by Root are the ideal relation between segments of the lower limb bone system, which must be met in order for gait to be of maximum efficiency. Once the criteria of normalacy are assessed, any deviation from these criteria signal the presence of a pathology. The main criteria of normalacy established for the human body in standing position are:

– bisector of the distal third of the lower limb is vertical,

– the subtalar axis is in neutral position: neither in pronation, nor in supination,

– bisector of the posterior surface of calcaneus is vertical,

– metatarsal joint is in maximum pronation,

– the metatarsophalangeal joint line is perpendicular to the bisector of the posterior calcaneus,

– the foot is rotated outward with an average angle of 7–10 degrees,

– no abnormal rotational or torsional influences in the lower limb,

– ankle joint allows a dorsiflexion movement of minimum 10 degrees.

Deviations from the criteria of normalacy of the biomechanical system may generate additional pressure in the lower limb structure resulting in development of pathomechanics. According to this paradigm, during the gait cycle, the subtalar joint must function as close to the neutral position as possible before heel lift-off (approximately 30% of the gait cycle).

Defining basic types of foot pathology is one of the major consequences of Root's model[6]. Thus, in relation to the basic criterion of Root's model – the neutral position of the subtalar axis – the following types of foot pathologies are identified:

1. forefoot invertus (forefoot varus and forefoot supinatus),
2. forefoot evertus, (forefoot valgus and plantarflexed first ray),
3. rearfoot varus,
4. rearfoot valgus,
5. equinus.

Pathologies associated with the above deformities may be: hallux valgus, hallux limitus, calcaneal spur, hammer toe, plantar fasciitis, sinus tarsi syndrome, calosities, posterior tibial tendon dysfunction, interdigital neuroma; genu valgum, patellofemoral dysfunction, tendinitis, etc. It should be noted that these pathologies are also found in diabetic foot.

The main critical aspects to Root's paradigm refer to[7–9]:

– intra- and inter-observer reliability of static biomechanical examination,

– applicability of criteria of normalacy to the population. Thus, 68% ± 1 Sdev [standard deviation] of the population must have the characteristics defined by the criteria of normalacy, which is contested by McPoil et al. because only 17% of 116 investigated subjects had met the criteria of normalacy,

– validity of the method for determining the neutral position by challenging the supination: pronation ratio of 2:1,

– dynamic behaviour of the subtalar joint; McPoil and Cornwall's[10,11] research findings demonstrate that the subtalar joint is maintained in a pronated position throughout the unilateral support phase, the transition from eversion to inversion occurring after heel lift-off the phase. These findings were confirmed in other works by using multi-segment models,

– difficulty to predict dynamic behaviour based on static tests.

Despite all the criticism mentioned and due to the lack of a single alternative, it should be mentioned that Root's paradigm is still part of the Podiatry training curriculum, especially in the United States, United Kingdom, Belgium, Spain and Australia, and is still the subject of much research on normal and pathological lower limb biomechanics[11,15] .

Sagittal Plane Facilitation Theory developed by Howard Dananberg, DPM, starting from the analysis of functional hallux limitus as functional foot pathomechanics , characterized by the fact that the hallux cannot fully perform the dorsiflexion movement required in order to achieve propulsion [30–60% of gait cycle][12–14]. A dorsiflexion movement of the hallux greater than 25–30° cannot be achieved without being accompanied by a plantarflexion movement of the first metatarsal. This functional incapability to perform tasks specific to propulsion during the gait cycle leads to the occurrence of compensatory movements associated with pathologies such as plantar fasciitis, posterior tibial tendonitis, flat foot, hallux valgus, tailor's bunion, patellofemoral syndrome or chronic back pain. In achieving an effective transfer of weight from one foot to the other, Dananberg highlights the importance of the pivotal movement around metatarsophalangeal joint I, as the last pivotal center of the existing 3 - heel, ankle and metatarsophalangeal joint I. Any blockage of the movement in the sagittal plane found in pathologies such as hallux limitus, functional hallux limitus or equine ankle, causes dysfunction-nalities in intrinsic joints of the foot and lower limbs due to inefficient adequate functioning of foot support mechanisms: midtarsal joint locking (high gear-low gear and calcaneo-cuboid joint locking mechanisms described by - Bosjen-Moller), windlass mechanism (Hicks), verticalization of the first ray, role of the swing limb in creating the power of motion.

Means of compensation generated by the dysfunction of foot mechanisms are[13,14]:

– apropulsive gait with delayed heel lift-off after contralateral foot contact,

– vertical lift of the foot off the supporting surface,

– avoiding loading the first ray by adopting a position of inversion and loading the lateral column of the foot,

– propulsion with the foot in abduction or adduction,

– flexed body position.

According to Dananberg, blocking the advance in the sagittal plane by functional hallux limitus may occur for very short times of the order of 100 msec, making it impossible to detect by visual analysis and imposing the use of pressure measuring instruments to determine the trajectory of the center of pressure. In addition to the development of clinical tests for the assessment of functional hallux-limitus, other indicators of this pathology are: distal phalanges in hyperextension, upward orientation of the hallux nail, callosities under the hallux and under the heads of metatarsals II and III.

Given the relation between hallux dorsiflexion and plantarflexion of the first metatarsal, the main goal of conservative treatment in the case of functional hallux-limitus is facilitating the plantar-flexion and eversion movement of the first metatarsal at the same time as the hallux dorsiflexion movement.

Tissue Stress Theory focuses on kinetic assessment of gait as opposed to the kinematic assessment considered the expression of Root's paradigm. Thus, for instance, reducing the pronation or supination speed becomes a more important parameter in the economy of conservative treatment than the pronation or supination degree measured in dynamics. Also, changing the strength and orientation of forces acting on the musculoskeletal system is necessary in order to reduce symptoms to the detriment of changes in position of elements of the same system. Starting from the limitations of Root's paradigm, Thomas McPoil, PT, and Garry Hunt, PT consider that by maintaining deformities in anatomical structures within the limits of elasticity, the subject may experience a tolerable degree of internal stress in the tissues[7]. Increasing loading or changing the level of activity will determine the shift of tissues from the elastic deformity area to the plastic deformity one, leading to microtrauma and symptoms associated with overuse. The mentioned authors propose a new tissue stress paradigm, establishing a 4-stage protocol[7,15]:

– stage 1: identifying anatomical areas where there is pain,

– stage 2: applying controlled stress on the previously identified areas of interest,

– stage 3: based on assessments, it is determined whether the pathology is mechanical,

– stage 4: prescribing conservative treatment with the objective of reducing stress in tissues by manipulations, changes in the level of activity and using medical devices, restoring the patient to the level of activity required for daily activities.

In the field of physiotherapy there is also physical stress theory proposed by Michael J Mueller, Katrina S Maluf regarding tissue adaptation to physical stress[16]. The basic premise of this theory is that changes in the physical stress level cause an adaptive response in all biological tissues.

The fundamental principles of this theory, of interest in the treatment of diabetic foot, are determined by defining a field of maintenance for tissues, where they function normally. Induction of stresses outside the field of maintenance causes a decrease or increase of tolerance to stress while excessive stress causes injuries.

The mechanisms by which the integrity or abnormal function of tissue is affected, also highlighted in the case of diabetic foot, are:

– high stress applied for a short time,

– low stress applied for a long time,

– moderate stress applied repetitively.

The limits that characterize the type of tissue response varies from individual to individual, physical stress being a parameter defined by size, time of application and direction of application.

The level of physical stress in tissues or their response to stress may be influenced by: motion and alignment, extrinsic factors (medical devices) and physiological factors.

Kevin Kirby, DPM, addresses conservative treatment of foot pathomechanics based on the study of rotational equilibrium of forces acting in relation to the anatomical axes of the foot joints and especially around the subtalar axis[17,18]. The pathological type of foot is defined in relation to the position of subtalar axis, resulting in “medially deviated subtalar joint axis foot”, equivalent to pes planus or “laterally deviated subtalar joint axis foot”, equivalent to pes cavus. Assessing the subtalar joint axis position in the transverse plane becomes an essential point of biomechanical examination, given that intrinsic forces – generated by lower limb muscles and the extrinsic ones – ground reaction force, will always seek to establish a balance of their actions exercised in relation to this axis. Thus, the resultant forces acting medially on the axis will have a supination effect, and those acting laterally will have a pronating effect, while the forces acting directly on the axis will have the effect of “pushing” or dorsiflexion. The position of calcaneus bisector in relation to the supporting surface – an important element in the clinical examination of Root's paradigm, becomes a poor indicator of the balance between the forces of supination and pronation. Based on tissue stress theory, Kirby and Fuller explain the principles of treatment of pathologies such as tarsus channel syndrome, plantar fasciitis, calcaneal spurs, hallux limitus, hallux valgus or posterior tibial muscle dysfunction[18,19].

Basically, by means of tissue stress theory, pathomechanical diagnosis implies determining the anatomy structure that generates pain due to excessive stress manifested in the three-dimensional structure of musculoskeletal system, while the goal of the treatment is to reduce excessive loads and to ensure normal functioning of lower limbs under static and dynamic conditions.

Neuromechanical theory

The increasing number of injuries of lower limbs as a result of practicing recreational sports has led to attempts to establish their development mechanisms. In 2001, Benno Nigg, Dr. Sc. nat., studying the effects of ground reaction forces on the lower limbs, proposed a new paradigm on the role of impact forces and pronation, also known as neuromechanical or preferred motion pathway theory[20,21]. At the time of the elaboration of this new theory, the main causes of the appearance of injuries were considered the excessive impact forces generated in the initial contact phase of the gait cycle and excessive pronation. The conservative treatment of these foot pathomechanics were based on the adoption of shock absorbing or motion control strategies using special designed sport shoes and foot orthoses/insoles. Ground reaction force is made up of two components: the impact force and the active force. The active force indicates that the movement is controlled by muscle activity and can be modified in order to ensure control of the movement. Impact force, called initially “passive force”, is determined by a pre-activation of the muscular system with the purpose of avoiding the expected effects of the contact with supporting surface. Unexpected instant change of the impact conditions can generate an inappropriate response of the musculoskeletal system to the new conditions. In scientific literature the term “passive” was replaced with “impact” to highlight the fact that muscular system is not passive but is ready to respond in accordance with the expectations in relation to the possible effects of the contact between the foot and the supporting surface[21].

In a synthesis of the results of research on the effectiveness of the shock attenuation mechanisms and pronation control in alleviating lower limb injuries, Nigg reveals some surprising conclusions, of which we mention[20,21]:

– maximum impact force and internal forces from foot structure, resulting from the contact between the foot and the supporting surface, are not influenced by the hardness of the material of footwear soles, but are influenced by the speed of running,

– running on hard surfaces did not materialise in an increase of injuries compared to running on soft surfaces,

– in terms of movement control, sports shoes and foot orthoses are producing small and insignificant changes, ranging between 2–4 °,

– use of foot orthoses has not caused changes in the alignment of the structure of the foot,

The presented results indicate that the impact forces and pronation cannot be considered as the main source of injuries during sports activities. Thus, the cause of trauma must be explained through other concepts such as the muscular system tuning and maintaining of the preferred pathway motion. In the concept of tuning of muscle activity, the impact force shall be assimilated with an input signal characterized by amplitude and frequency. The impact causes vibrations of bone and muscular systems of the lower limbs. The muscular system is the most exposed because of the natural frequency (10–20 Hz) lower than that of the skeletal system (60–2 kHz), but the same size order with that of the impact force, making possible the appearance of the phenomenon of resonance. The phenomenon of resonance is associated with discomfort, high energy costs of gait and increasing the risk of injuries. That is why the human body must take appropriate measures to avoid the appearance of resonance through the adoption of a muscle tuning strategy evidenced by modification of the muscle’s electromiographical parameters. Changes in the frequency of the input signal and specific one of the soft tissues can be obtained by changing the contact surface mechanical properties, running shoes soles or running style, through training or by wearing compressive systems[20,21].

On the basis of the above exposed consideration Nigg elaborates and proposes the neuromechanical paradigm based on the concepts of “muscle tuning” and “preferred movement pathway” in which impact forces are the equivalent of an input signal at the level of the human body that produces a reaction of adaptation-adjustment of the muscle activity. The adaptation of muscle activity occurs in a very small time interval before the next contact with the support surface, the body acting for the maintenance of the activity’s specific favorite way of movement (running, walking, etc.) and minimizing soft tissues vibrations. If adaptation is in agreement with the preferred way of movement of the joint, then the intensity of the muscle activity can be reduced; if adaptation is contrary to the preferred mode of movement, then the intensity of the muscle activity will increase. An optimum conservative treatment must have as its objectives to reduce the intensity of muscle activity induced by pathomechanics. Based on the properties of the input signal and the subject specific characteristics the adjusting of the muscular activity takes place.

According to this theory, the devices used in the conservative treatment act as filters for input signal represented by impact forces. Plantar surface of the foot captures through its mechanoreceptors the external signal external filtered which is transmitted to the central nervous system. Central nervous system produces a dynamic, individualized response. On the basis of the response provided by the central nervous system, necessary tasks are carried out. The objectives of using footwear and in-shoe devices in the conservative treatment of foot pathomechanics are to influence the activity of the muscles, reducing the load on joints, improving comfort and improving performance. According to Nigg, demonstration of the validity of this theory requires further studies.

CONCLUSIONS AND FUTURE PROSPECTS

The study of the foot functioning paradigms is a prerequisite for the prescription of an functional conservative treatment for foot pathomechanics.

The evolution of the thinking models was originally based mainly on clinical observation and evolved as biomechanical analysis has advanced, often to the invalidation of the clinical observations. In this work a brief presentation of the most representative foot functioning paradigms was attempted. The importance of studying these thinking models is even more significant in the case of diabetic foot, as recent research emphasizes the evaluation of internal tissues stresses, which are considered one of the important causes of foot ulcerations. The lack of a unified theory to explain the normal and pathological foot biomechanics is demonstrating the importance and complexity of the study of the functional-conservative treatment of foot pathomechanics.

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