THEORY AND METHOD FOR FUNCTIONAL REHABILITATION OF THE FIRST METATARSOPHALANGEAL JOINT

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Limitation of motion at the first metatarsophalangeal joint (MPJ), hallux limitus or rigidus, can occur for various reasons.[1] This limitation will alter the normal gait pattern, which may directly affect more proximal joints as compensatory motion is required. Abnormal increases in motion across these adjacent joints will lead to more stress and strain on the joint and periarticular structures. The long term result of this abnormal strain is inefficiency of gait and early fatigue, hastened degeneration of the joints, and pain associated with tendonitis and fasciitis. This adds to the detrimental functional effects of the primary joint pathology, leading to a prolonged if not permanent course of convalescence and activity modification.

Loss of motion at the first MPJ is encountered relatively frequently by podiatric and orthopedic physicians. When this loss is due to identifiable joint restriction secondary to osseous pathology (e.g. exophytic spurring, joint deviation as with hallux valgus, joint dislocation, etc.), the pathology is directly addressed through surgery or by some other means to restore motion. It is also common after the initial treatment of this condition to institute some form of physical therapy and rehabilitation program to prevent further loss of motion. In cases where soft tissue binding or scarring has resulted in this limitation, often the latter approach is initiated before surgical intervention is undertaken. For example, iatrogenic joint restriction stemming from hallux valgus repair would warrant aggressive range of motion exercises and other joint mobilization efforts. When these efforts fail, further surgical intervention such as manipulation under anesthesia or arthroplasty may be indicated. Clearly the importance of adequate rehabilitation of the joint can be appreciated, whether as an adjunct to, or in prevention of surgery.

Functional rehabilitation of the first metatarsophalangeal joint describes the process of recreating the normal physiologic movement of this joint as seen in normal gait through external means, to provide or restore motion at this essential joint. The first metatarsophalangeal joint functions as a gliding joint, and consequently the axis of rotation is continuously changing as the hallux dorsiflexes on the metatarsal. It is necessary for the metatarsal to plantarflex during this motion to allow the proximal phalanx to complete its arc of motion without impinging on the dorsal aspect of the metatarsal head. The axis that defines the actual motion of the first metatarsophalangeal joint is an inverted J-shape. True functional rehabilitation of this joint, stretching the joint the way it would anatomically, recreates and obeys this axis of motion, rather than attempt to move the joint through non-physiologic axes.

BIOMECHANICS

There is a common assumption that joint motion in the foot and ankle describes the distal segment moving on the stable proximal segment. In the case of the first MPJ the term dorsiflexion is used to describe motion of the hallux towards the tibia. Likewise, the term hallux limitus refers to a limitation of this ability to close the angle between the long axis of the first metatarsal and the long axis of the hallux as the hallux moves towards the tibia (ie, limitation of hallux dorsiflexion). However, this descriptive term is not necessarily applicable in this situation, at least not in the traditional sense.

As the moving body thrusts forward and enters into the propulsive phase of gait, there is a weight transfer from the lateral foot across the metatarsus towards the first ray. At this point the foot is converting from a mobile adapter to a rigid lever in preparation for propulsion.[1] The peroneus longus tendon is firing to plantarflex and stabilize the first ray and assist in raising the lateral column for medial load transfer. The hallux, which is the last digit to purchase the ground during midstance and to leave the ground at toe off, is passively dorsiflexing at this point. This is a crucial principle in the understanding of hallux limitus.

The long extensor tendon to this toe has not begun to fire yet the body continues its forward momentum over the fulcrum of the midfoot. This sagittal plane motion is seen at the near transverse axes of the metatarsophalangeal joints and the ankle joint. Heel lift occurs as the body swings over the plantigrade foot like a pendulum, and is assisted by active firing of the posterior musculature (triceps surae and long flexor tendons). The hallux is stabilized primarily by the firing of the posterior muscle group. As the flexor hallucis longus fires the hallux attempts to plantarflex against the stable ground. Consequently the hallux, while pressing against the immobile substrate, effectively dorsiflexes passively on the metatarsal as the rearfoot is lifted and the forefoot maintains contact via the hallux.

MODELS OF FIRST MPJ MOTION

The sagittal plane motion of dorsiflexion occurs at the metatarsophalangeal joint because the joint axis is in the transverse plane (perpendicular to the direction of movement). If the axis of this joint was stationary, it would function like a hinge to allow the proximal phalanx to rotate around. This hinge axis would lie somewhere in the center of the metatarsal head (Figure 1). If the metatarsal were to stay stationary while the hallux completed an arc of motion around a static hinge axis then this type of motion would result in a jamming effect as the hallux dorsiflexes. The dorsal aspect of the phalanx would move dorsally and proximally as the hallux dorsiflexes because of the ball and cup relationship of this joint. With proximal movement the phalanx would engage the metatarsal head at some point, resulting in an abrupt end point to motion with impaction of the phalanx on the metatarsal head. We know that this would not normally occur. Consequently a more realistic model of the first MPJ mechanics demonstrates more of a gliding motion rather than a hinging or pivoting motion. A gliding axis in the transverse plane of the metatarsal can be stationary. A model of this type of movement would be a rope of finite length that tethers between a point in the middle of the head of the first metatarsal and the middle of the base of the proximal phalanx (Figure 2). The phalanx would glide on the head of the metatarsal independent of the position of the metatarsal. In reality, when the first metatarsal is in a relatively dorsiflexed position, whether held there manually, or in a forefoot varus deformity, there is severe and abrupt restriction of the arc of motion that the hallux can travel through. Normally there is no abrupt restriction of motion of this joint. In fact there is additional freedom of motion afforded to this joint by way of the first metatarsal plantarflexing in relation to the long axis of the hallux, a point which will be discussed in more detail below. This occurs during midstance and into the propulsive

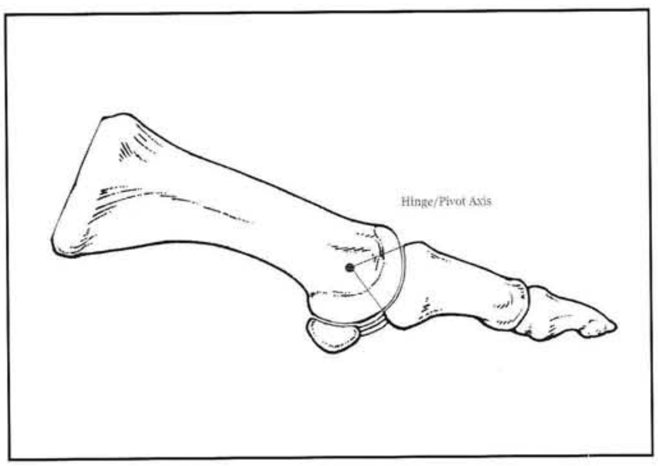

Figure 1. Hinge/Pivot Axis Model. The proximal phalanx pivots on the stationary metatarsal axis. This does not occur because the phalanx normally clears the dorsal metatarsal head, and the metatarsal moves during ambulation, resulting in a moving axis. Additionally, the hallux does not move during early propulsive gait when the metatarsal remains stationary.

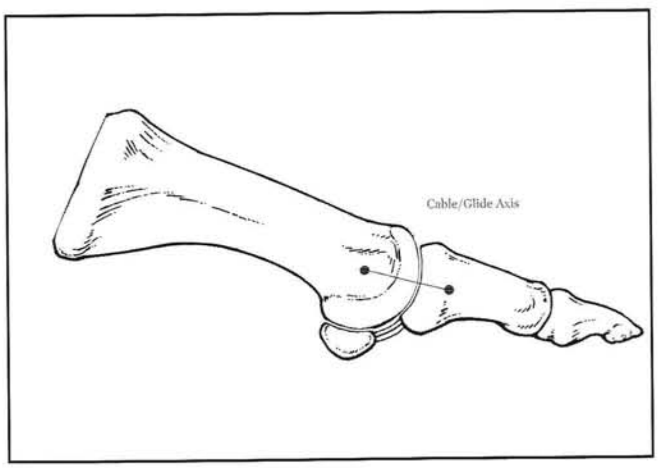

Figure 2. Cable/Glide Axis Model. The proximal phalanx glides on the stationary metatarsal head, supported by a tensioned cable. This does not occur because the hallux does not actively move during early propulsive gait while the metatarsal remains stationary. If the cable were affixed to the stationary metatarsal, it would be necessary for the hallux to actively move to achieve dorsiflexion at the metatarsophalangeal joint. Additionally, there would be no requisite movement of the metatarsal as the proximal phalanx reached the dorsal boundary of motion. This movement in fact does occur, negating the fixed cable model.

period, when the peroneus longus and flexor hallucis longus muscles are actively firing to stabilize and plantarflex the first metatarsal and stabilize the hallux respectively. This combination of actions allows for the most dorsiflexion possible at this joint.

Plantarflexion of the first metatarsal occurs simultaneously with loading and passive dorsiflexion of the hallux. Because the long axis of the first metatarsal and center of the metatarsal head are moving in relation to the long axis of the hallux, the axis of the first metatarsophalangeal joint cannot be stationary. The instant centers (axes) of this gliding motion of the hallux as it dorsiflexes on the first metatarsal head can best be traced along a curve described by an inverted J (Figure 3).

CLINICAL USE OF THE J-AXIS JOINT MODEL

Because the normal biomechanics of this joint follows the J-type pattern then rehabilitation efforts should likewise attempt to reproduce this motion. Appropriate therapy then would be designed to actively plantarflex the first metatarsal while passively dorsiflexing the hallux, rather than actively dorsiflexing the hallux and neglecting the first metatarsal. Active metatarsal plantarflexion is descriptive of closed kinetic chain exercise, a more functional, biomechanically correct method of restoring lost motion at the first metatarsophalangeal joint.

The Hallux Extensionator® is designed to provide a gentle though forceful plantarly directed load to the metatarsal segment while the hallux is stabilized against a passive restraint (Figure 4). This will effectively recreate the gliding J-axis seen normally at the first metatarsophalangeal joint, allowing for maximal stretch on contracted tissues. The hallux can be brought into its position of maximal dorsiflexion. This high load across the periarticular structures is performed over short duration with repetition, using a Variable Load/Variable Position principle known as Patient-Actuated Serial Stretch, or PASS.[2]

There are other models for rehabilitation of this joint that have been utilized with varying degrees of success such as Continuous Passive Motion (CPM), Low-Load Prolonged Stretch (LLPS), and Static Progressive Stretch (SPS). CPM devices such as the T-300 Great Toe CPM from Jace Systems™ can bring the hallux through its entire arc of motion. CPM is designed to maintain existing motion, not increase it. DynaSplint® Systems' Toe Unit uses the Low-Load Prolonged Stretch principle, which is best described as Static Load/Variable Position. The patient applies the spring-loaded device for six to twelve hours a day, over a period of up to 4 months. The DynaSplint® Toe Unit can achieve up to 2 foot-pounds of torque across the MPJ while stretching tissues through the 9+ weeks of connective tissue remodeling. Static Progressive Stretch is a principle employed by Joint Active Systems (JAS), and applied in the rehabilitation of other joints. SPS is another

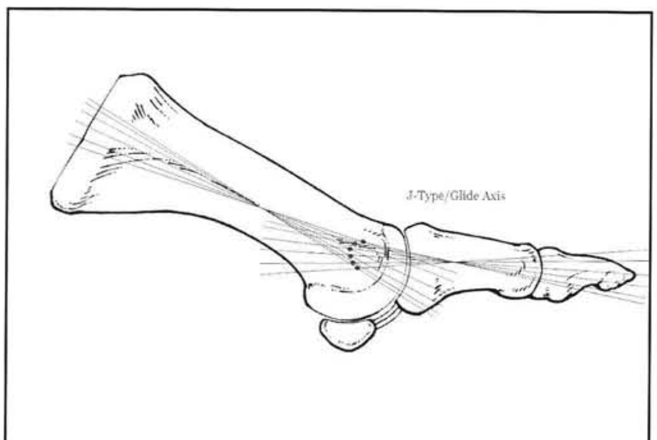

Figure 3. J-Type/Glide Axis Model. The proximal phalanx effectively remains stationary, while the metatarsal actively plantarflexes. The hallux passively dorsiflexes, gliding on the metatarsal head, without dorsal jamming or motion restriction. The long axis of the metatarsal head retracts proximally and inferiorly as the metatarsal plantarflexes. A line tracing the instant centers of motion describes an inverted J shape. Under this model, the phalanx and sesamoids can remain stationary during propulsion, while dorsiflexion can occur.

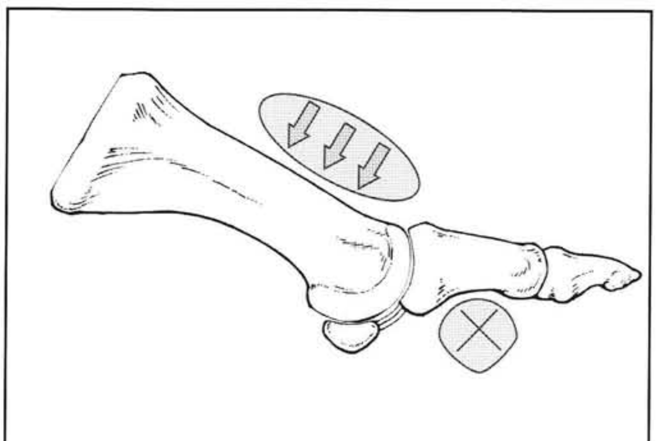

Figure 4. Design Scheme for the ERMI Hallux Extensionater®. Active plantarflexion of the metatarsal segment is achieved by an inflatable air bag over the dorsum of the foot which depresses the metatarsal proximal to the MPJ. Passive restraint of the hallux and offloading the sesamoids results in dorsiflexion of the phalanx and sesamoid complex.

form of low load application over prolonged periods. The Hallux Extensionater® from ERMI, Inc. uses Variable Load/Variable Position PASS model which is focused on progression only of end range of motion. The device can produce as much as 25.83 foot-pounds of torque across the first MPJ depending on joint position, stretching the boundaries at the end range of motion. The Hallux Extensionater® is the only device on the market that can achieve this substantial force to stretch scar tissue, and is the only device that allows for joint recovery during therapy. Continued use of the device will attempt to increase motion rather than preserve motion.

TREATMENT WITH THE HALLUX EXTENSIONATER® DEVICE

The foot is placed comfortably within the confines of the device, and the device is fitted to the appropriate length for the patient's foot. The leg and forefoot are secured to the frame assembly, with the foot at approximately 25 degrees of ankle plantarflexion to eliminate the tethering force of the posterior muscle group, specifically the long flexor tendons. The heel rests within a padded cradle designed to support the heel while allowing supination/inversion with stretch of the windlass mechanism of the foot. The hallux rests on the padded quarter-cylinder, crescent shaped crossbar, with the sulcus at the interphalangeal joint level comfortably supported. A forefoot strap is secured over the dorsum of the foot, across the metatarsal segment. The strap is also secured to the frame on either side of the foot. Affixed to the undersurface of this strap is an inflatable airbag approximately the width and length of the distal metatarsal segment attached to a bulb for air delivery. Three point contact with the foot is established, with stationary ends and motion in the middle. The patient will control inflation and deflation of the air bladder throughout the course of treatment. As the airbag inflates, the metatarsal segment is actively depressed, while the hallux passively dorsiflexes against resistance, recreating the physiologic motion seen in normal active gait. By using an airbag encased in padding, the force is dispersed evenly across the dorsum of the foot without crushing the delicate tendinous units. The rotating crossbar allows for comfortable dorsiflexion without shear forces across the pad of the hallux.

High loads can be delivered rapidly or slowly with pain to the patient being the appropriate guide for pressure application. This is the principle behind Patient-Actuated Serial Stretching. High loads in a physiologic manner can be applied to overcome arthrofibrosis, adhesive capsulitis, frozen sesamoids, or other conditions. Lower loads can also be applied repeatedly for active excersise of the MTPJ, such as after hallux valgus surgery or joint injury. Because the Hallux Extensionater® is designed to apply high loads over short periods of time, the therapeutic program will be shorter in length than the traditional low-load, prolonged stretch of other splints currently on the market, while providing more measurable results sooner.

Because the patient controls the amount of force applied by controlling the amount of air delivered to the airbag, they have direct control over their own therapeutic program, which should lead to increased patient compliance. Having control over their treatment is psychologically reassuring; the more they use the machine, the more quickly they will recover. Results should be apparent rather quickly, and the patient should be able to see and feel immediate results.

DISCUSSION ON THE IMPLEMENTATION OF THE NEW CLINICAL MODEL AND APPARATUS

Joint restriction at the first metatarsophalangeal joint is a relatively common condition seen by practitioners who treat foot pathology. Methods for non-surgical management have revolved around symptom management (i.e., orthotics and rocker-bottom shoes) and aggressive physical therapy. This latter treatment has come under scrutiny because of the phenomenon of 'desensitization,' whereby joint motion does not increase, but the symptom of pain and overall perception of the stiffness become less severe.

For therapy, we would prefer to restore lost motion, rather than accommodate for it. Our review of the anatomic structures and their biomechanical significance lead us to a convincing model for functional first metatarsophalangeal joint motion. The concept of the metatarsal moving on the phalanx rather then the opposite was a crucial turning point in determining how to recreate this motion for more accurate joint mobilization. An apparatus was then developed to actively plantarflex the metatarsal while stabilizing the foot at the heel and at the hallux, with increasing force delivered as the boundary of motion was encountered. A mathematical model of the device was constructed from clinical information which supported objective and subjective evidence of increased torque at the end range of motion. The results of this study are included in a subsequent chapter.

Clinical trials with this apparatus are currently underway. Early results show outstanding clinical improvement in range of motion and decreased symptomatology at the first metatarsophalangeal joint. Long term follow up will be necessary to determine if the initial increase in motion will remain. Data as far out as six months suggest that the increased motion is permanent, although this has not been statistically analyzed. The results of these and other clinical studies will be the focus of subsequent research.

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