Biomechanics of the Diabetic Foot: Consideration in Limb Salvage

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Significance: The biomechanics of the diabetic foot is altered and maladaptive. We lack a thorough understanding of the functional consequences of limb salvage. We currently rely on observation and descriptive data pertaining to the biomechanics of the diabetic foot.

Recent Advances: Technology has driven our ability to objectively describe biomechanics of the diabetic foot. Dynamic, segmental, gait analysis in conjunction with peak plantar pressure measurements have provided valuable insight.

Critical Issues: The biomechanical pathogenesis of a chronic ulceration that necessitates limb salvage is difficult to capture. The subsequent changes that occur after limb salvage are even more difficult to understand. However, methodical biomechanical analysis over the past several decades have provided a deeper understanding of diabetic foot function.

Future Directions: Ultimately, a better understanding of the biomechanics of the diabetic foot would allow us to better select the most appropriate amputation level and maximize function after limb salvage attempt.

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SCOPE

A PRINCIPAL GOAL of limb salvage surgery is to preserve as much of the bone and surrounding soft tissue structures as possible in order to maintain function. Therefore, an understanding of the biomechanics of the diabetic foot is very important in the context of limb salvage. The biomechanics of the diabetic foot is different from that of the nondiabetic foot. Fundamental changes occur in the overall gait with specific maladaptive processes occurring in the diabetic foot.¹ These maladaptive processes are both structural and functional in nature. Structural changes include changes in the soft tissue on the plantar aspect of the foot.^{2,3} More pertinent to this discussion are the changes to the anatomical structures related to function such as those encountered in the

capsular and tendinous structures of diabetics.³⁻⁵ These alterations can lead to inefficiencies in gait and the lack of accommodation to the ground during weightbearing. This inadaptible foot causes focal areas of high pressure and susceptibility to shear forces. The result is the formation of chronic ulcerations, delayed or non-healing surgical incisions, and ulcer recurrence after limb salvage attempt.

TRANSLATIONAL RELEVANCE

Animal models are not appropriate for the study of the biomechanics of the human foot. However, insight into the mechanisms of soft tissue changes in an elevated glucose state allows us to make valuable inferences. Evaluation of the biomechanics of the human foot is unique;

therefore, experimental models have significant limitations and cannot truly reflect its dynamic nature. Computer simulation of gait patterns, and motion capture imaging allows for some degree of gait examination. However, the complexity and individuality of foot biomechanics does not lend itself easily to precise or detailed analysis. Cadaveric examinations exploring joint motion and anatomical relationships also have their limitations for these are static in nature and do not accurately reflect perfused soft tissue structures.

BACKGROUND

A detailed analysis of the deleterious biomechanical process involved in the diabetic foot is beyond the scope of this review. However, one of the main causative factors in the altered biomechanics of the diabetic foot is peripheral neuropathy.⁶ In the environment of a diabetic foot, the normal proprioceptive and protective abilities are compromised and become almost entirely absent as the disease progresses. In this way, peripheral neuropathy directly contributes to joint subluxation and the lack of accommodation to ground reactive forces. The foot makes subtle adjustments during gait based on its sensory feedback. Due to peripheral neuropathy, this feedback is short-circuited. For example, while a person is in a standing position, the foot and the body make minor adjustments to decrease prolonged pressure to one area. During ambulation there are greater forces at work, which exponentially increase the potential for problems.

The biomechanics of the foot is a complicated and broad subject; hence, it is well beyond the scope of this article. However, a basic understanding of foot biomechanics is needed and will be reviewed in the following sentences. The swing and stance phases of gait are the two major components of ambulation. The swing phase of gait involves a nonweightbearing period when one limb clears the ground and advances forward. The stance phase of gait begins at heel contact and ends with the lift off of the toes from the ground. The stance phase of gait occurs when one limb bears the entirety of the body's weight. The heel takes the initial impact on the ground and the weight is then transferred forward to the balls of the foot and toes as the body propels forward. Initially, during the stance phase of gait, the foot is more flexible, allowing it to absorb shock and adapt to the terrain. The foot then transitions to a rigid lever by flexing or extending the intrinsic (originating and terminating within the foot) and extrinsic (originating proximally on

the leg and terminating within the foot) muscles, which stabilizes the joints, allowing for plantar-flexory force transmission needed to propel the body forward.

Joint immobility plays a pivotal role in the faulty biomechanics of the foot and ankle in the diabetic patient. Structural changes occur within the tendon and capsule of the diabetic patient. A disorganized pattern emerges in the diabetic tendon, capsule, and ligament.^{5,7,8} These changes lead to decreased elasticity and tensile strength. This in itself may not be problematic. However, these changes lead to either instability at joints causing subluxations or overall stiffness of the foot. In either case, the result is poor foot biomechanics. An example of an unstable diabetic foot is Charcot neuroarthropathy, which is typified by joint subluxations. The loss of normal architecture leads to the development of bony prominences on the plantar aspect of the foot causing the formation of chronic ulcerations. A key contributor in the Charcot neuropathy process are the changes that occur in the Achilles tendon resulting in an equinus deformity.⁹ An equinus deformity is defined as a contracture of the Achilles tendon. The upward force of the Achilles tendon during propulsion, in an environment of a contracture, causes a break or subluxation in the midfoot. At the other end of the spectrum, a stiff or immobile foot caused by joint capsule contracture is also maladaptive causing focal areas of high pressure, which again leads to the formation of chronic ulcerations.

CLINICAL PROBLEM ADDRESSED

The downward cascade of biomechanical abnormalities culminating in chronic ulcerations necessitating limb salvage is a significant problem. Therefore, early identification of biomechanical faults is an important component in the overall care of the diabetic foot. A thorough physical and radiographic examination of joint relationships is critical in identifying potential problem areas (Fig. 1). A fundamental part of the physical examine involves inspection of the plantar aspect of the foot for any discrete or diffuse calluses that may indicate focal areas of high pressure or areas of increased shear forces. Plantar pressure measurements in the diabetic foot have been well studied. A direct correlation between ulcerations and areas of high pressure has been established.¹⁰ The measurement of plantar pressures provides some insight, although limited, of the underlying biomechanics of the foot

Figure 1. General pathway of where the biomechanical examination fits in the environment of limb salvage.

during gait. Further, assessment of the range of motion of each joint of the foot will allow for examination of joint mobility and joint capsule stiffness. The hypermobility of a joint(s) can lead to disproportionate transfer of plantar forces to the surrounding areas as the affected segment(s) elevate in response to ground reactive forces. Conversely, joint immobility contributes to areas of higher pressure as well. Rao *et al.* have recently demonstrated this phenomenon in a multi-segment kinematic model.¹¹ Radiographic assessment of bone alignment and relationships through weightbearing films is critical in identifying joint subluxation and bony prominences. Further, gait analysis is critical to identifying abnormalities. This involves observing the diabetic patient while ambulating without shoes. Forefoot (metatarsals and phalanges) to rearfoot (talus and calcaneus) relationships should be assessed as well as a visible collapse of the midfoot (cuneiforms, cuboid, and navicular).¹² This is exemplified in Hastings *et al.*, who have demonstrated an increase in duration of loading on the medial column (Hallux, first metatarsal, medial cuneiform, navicular, and talus) during ambulation in diabetics with peripheral neuropathy.¹³

The maintenance of adequate biomechanics after limb salvage poses a significant challenge. Limb

salvage often involves amputation of the digit(s) or other segments of the foot. It is extremely difficult to predict the resultant alterations in the biomechanics after amputation. The challenge is to create a biomechanically stable foot that has the least potential for further breakdown. In general, a shortened foot leads to a decrease in overall efficiency of the foot with global imbalance.¹⁴ The decreased efficiency has profound local and systemic effects, including increased load on the cardiovascular system.¹⁵

The concept that the partially amputated foot is imbalanced is critically important. The normal foot is balanced with both extrinsic and intrinsic tendinous attachments. The loss of a tendinous attachment through amputation may lead to the overpowering of the apposing muscle group. This results in a rotation of the foot in one direction or instability at other joints in the foot.¹⁶ For example, if the base of the fifth metatarsal is removed, there is no longer a distal attachment of the peroneus brevis muscle, which normally functions to evert (outwardly rotate) the foot. Therefore, the inverters such as the tibialis anterior and tibialis posterior are unopposed causing the foot to internally rotate in the frontal plane. This leads to increased pressure on the outside of the foot. Even though the limb may have been initially salvaged, over time a

new ulcer is likely to develop on this portion of the foot necessitating further surgery.

DISCUSSION OF FINDINGS AND RELEVANT LITERATURE

The biomechanical effect of segmental foot loss is profound. Initial limb salvage may be a short-lived victory if future further breakdown is highly likely. It is not enough to just preserve tissue; one must carefully consider the effects of surgery on biomechanical stability. Unfortunately, there is a paucity of data on the biomechanical ramifications of limb salvage procedures. Much of the medical literature is replete with conjecture, inferences, and theories. This is not surprising considering that the fundamental concepts of normal foot biomechanics are largely theoretical.^{16–18}

There is literature to support the concept that partial foot amputation is correlated with poor biomechanics. The alteration in biomechanics appears to be irrespective of the level of foot amputation. For example, there have been measurable increases in the pressure experienced sub first metatarsal head, lesser metatarsal heads and toes after a hallux amputation.¹⁹ Plantar pressures have also been measured to be significantly increased after digital amputation and ray resection as compared with controls attributed to compensatory biomechanical changes.²⁰ Further, peak plantar pressures were found to be increased after a transmetatarsal amputation.²¹ It is important to acknowledge that after a partial foot amputation is performed and appropriate orthotics and prosthetics are utilized, significant biomechanical changes are still present.¹⁴ The above-cited studies were largely based on plantar pressure measurements. Although the information gleaned is important, they do not address the overall biomechanical instability observed after limb salvage.

INNOVATION

The use of technology in evaluating the biomechanics of the foot is advancing. Three-dimensional, segmental, motion capture analysis in conjunction with more precise dynamic plantar pressure measurements have advanced the knowledge of biomechanics.²² However, the descriptive nature of these studies limits interpretation.

TAKE-HOME MESSAGES

Basic science advances

None directly applicable to the study of biomechanics and the diabetic foot.

Clinical science advances

As outlined in this discussion, there has been growing knowledge in the field of biomechanics specifically looking at altered function of the diabetic foot.

Relevance to clinical care

- Appropriate biomechanical examination is essential before and after limb salvage.
- The goal is to prevent ulcer recurrence or new ulcer development at another location by addressing biomechanical imbalances through custom foot and ankle devices and elective surgical procedures.
- It is not only important to salvage the foot, but it is as important to provide a functional foot.

CAUTION, CRITICAL REMARKS, AND RECOMMENDATIONS

Amputation or removal of specific segments of the foot will lead to biomechanical changes that may necessitate further limb sparing surgery. Therefore, careful thought before resection of bone and soft tissue must be conducted. Further, post-operative accommodation through foot and ankle devices is necessary. These devices include multi-density accommodative and/or functional orthotics with toe or foot fillers, extra-depth shoes with wide toe boxes, or ankle-foot orthoses. These devices are designed to off-load pressure and provide stability.²³ Our experience has demonstrated that bracing that crosses the ankle joint is preferable after transmetatarsal and Chopart's amputations because the remaining foot segment is relatively short which significantly decreases functionality and creates imbalance. These devices are absolutely essential in the prevention of future ulcerations. Further, elective surgical procedures to correct imbalance should be seriously considered.

Although the focus of this discussion is on foot biomechanics, it is important to evaluate the biomechanics of the whole body as well. Overall gait is altered in the diabetic patient manifesting in decreased speeds and variability in their steps.¹ Further, the issue of joint immobility extends beyond the foot and has significant effects throughout the body. Sawacha *et al.* have reported a decrease in mobility in a number of joints proximal to the foot and ankle in diabetics utilizing three-dimensional gait analysis.²² The position and function of each skeletal segment, including the knee, hip, and spine, will directly influence foot biomechanics. The inverse of this is true with faulty foot biomechanics after limb salvage causing detrimental effects up the skeletal chain.

FUTURE DEVELOPMENT OF INTEREST

Further development of technology and well-designed studies are needed to assess the biomechanical changes in the diabetic foot especially after limb salvage. We can gain some insight by evaluating plantar pressure measurements. However, they are restricted to the measurement of vertical forces. The development of a practical device that accurately, efficiently, and consistently measures shear forces would provide additional valuable information. Further, real-time, dynamic imaging of the underlying bony structures would provide a much better understanding of the biomechanics of the foot. However, until technology is developed that minimizes or eliminates the use of radiation for this type of imaging, we will continue to rely on markers placed on the surface of the skin in order to make inferences about joint motion. It is clear in the context of segmental foot loss there are significant biomechanical consequences. Researchers continue to work to better understand these consequences aided by advancing technology.

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