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UNDERSTANDING ELASTIC AND PLASTIC DEFORMATION IN MUSCULOSKELETAL INJURY

The structural tissues of the human body, including bone, cartilage, muscle, tendon, ligament, fascia, adipose, and skin, are subjected to both external and internal loading forces during our daily weightbearing activities. External forces originate from outside the body, such as ground reaction force (GRF) acting on the plantar foot during weightbearing activities. Internal forces originate from within the body, such as bone and joint compression forces, or tendon, ligament, and fascia tension forces.

The foot is routinely subjected to more external forces than any other structure of the human body. During bipedal standing, the external force from GRF on each foot is one-half times body weight (BW) and during one-leg standing, GRF is equal to 1.0 BW. However, during walking, running and sprinting activities, the external forces acting on the plantar foot are greatly magnified with peak GRF being about 1.25 BW during walking and about 2.5 BW during running (Keller TS et al.: Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. Clin Biomech, 11:253-259, 1996). Additionally, during sprinting, the external forces acting on the plantar foot as GRF have been measured to peak as high as about 5.0 BW (Udofa A et al.: Ground reaction forces during competitive track events: A motion-based assessment method. ISBS Proc Arch, 35:120, 2017).

These large external forces acting on the plantar foot as GRF during weightbearing activities result also in relatively large internal forces within the structural components of the foot and lower extremity. For example, during walking the plantar soft-tissues, plantar aspects of the calcaneus, metatarsal heads and digits, and bones of the foot and lower extremity are all subjected to compression forces due to the effects of GRF acting on the plantar foot. In addition, the muscles, tendons, ligaments, and fascia of the foot and lower extremity are subjected to internal tension forces as they either accelerate, decelerate, or stabilize the motions of the joints within the foot and lower extremity in response to GRF. In other words, external forces acting on the plantar foot as GRF cause internal compression, tension, and shearing forces within the structural components of the foot and lower extremity in response to GRF.

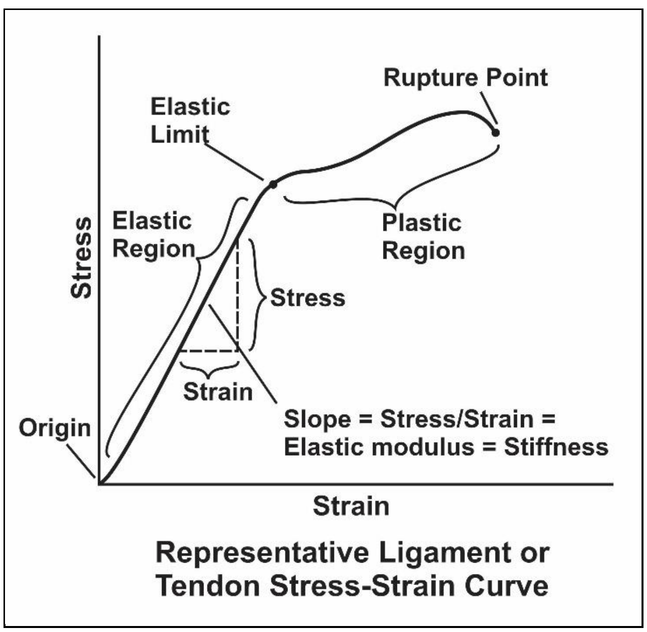

Figure 1. A representative stress-strain curve for a ligament or tendon will show, at low loads, an elastic region where the tissue will return back to its original shape once that load is removed. However, at higher loading forces and tissue stresses, the ligament or tendon will undergo tearing or rupture, indicating that plastic deformation of that tissue has occurred.

When an external force is applied to any object, both *stress* and *strain* will occur within that object. *Stress* is that ability of a material to develop internal resistance force in response to an external loading force and is measured in units of force divided by the cross-sectional area of the force. Larger forces acting over smaller surface areas of the object will cause increased stress. On the other hand, *strain* is the amount of relative deformation of a material and is measured as a dimensionless ratio of the amount of deformation of the object divided by its original length (Fig. 1). Objects that undergo large amounts of deformation under load will have higher strains (e.g., rubber band being stretched) than objects that deform little under the same external load (e.g., steel wire). Stress and strain are important biomechanical measurements that determine how an object, or one of the structural components of the foot and lower extremity, respond to external loading forces (Ozkaya N and Nordin M: *Fundamentals of Biomechanics: Equilibrium, Motion and Deformation. 2nd Edition.* Springer, New York, 1999, p. 128-131).

In the biomechanical laboratory, stress and strain are measured in a device called a *materials testing machine* where a piece of bone, cartilage, tendon, ligament, fascia, adipose, or skin may be either compressed or stretched under controlled condition so that both the external force and deformation of the material may be very precisely measured to determine its *load-deformation characteristics*. In order to determine the load-deformation characteristics of a bodily tissue, a graph, a *stress-strain curve*, is utilized which plots the amount of strain a tissue undergoes as it is subjected to a certain level of stress (Fig. 1). This stress-strain curve not only measures the inherent *stiffness* (i.e., resistance to deformation) of the tissue being tested but also can determine whether the tissue, while being deformed, is undergoing *elastic deformation* or *plastic deformation.*

By definition, if a material, or bodily tissue, is undergoing elastic deformation, it will deform a certain amount when the external load is placed upon it, and then will return back to its original shape when that external load is removed. An excellent example of elastic deformation is the stretching of a rubber band where an external tension loading force is applied to the rubber band to stretch it, and then, when that tension load is released, the rubber band will return back to its original shape. For any material or bodily tissue, the ratio of stress/strain is a fundamental mechanical characteristic of that material or tissue and is known as the *elastic modulus* (or *Young's modulus*) of that material or tissue. Plotted on the stress-strain curve, the slope of the initial part of the curve is equal to the value of the elastic modulus of the material or tissue and also represents the *stiffness* of the material or tissue (Fig. 1). Materials or tissues with steeper slopes have higher stiffness and materials or tissues with shallow slopes have lower stiffness. The term *compliance* is the inverse of stiffness with tissues of high stiffness having low compliance, and vice versa (Ozkaya and Nordin, p. 133).

Also noted on the stress-strain diagram at higher external loading forces (i.e., higher internal stresses) on the tissue, is a change in the slope of the curve from being more steep to more shallow, indicating decreased stiffness (or increased compliance) within that material or tissue (Fig 1). This change in stiffness at higher external forces will also, many times, be accompanied by a change in the molecular structure of the tissue that prevents it from not being able to return back to its original shape once the loading force is removed. This permanent deformation of the tissue at larger magnitudes of external loading forces is known as *plastic deformation*, which may cause the tissue to rupture, tear or fracture (Ozkaya and Nordin, p. 135-139).

Very important in this discussion is the concept that structural tissues of all animals, including humans, must remain undamaged in order to avoid injury. For example, if a bone is loaded by a compression force, it will shorten slightly in response to that force and then, once compression force is removed, will lengthen back to its original shape. In addition, if a ligament or tendon is loaded by a tension force, it will lengthen in response to that force and then shorten back to its original length when the tension force is removed. In order to remain injury free, the bodily tissues must operate at relatively low stress levels, which are elastic in nature, and not at the larger loading forces which can cause plastic, or permanent, deformation of that tissue.

In other words, if our bone, cartilage, muscle, tendon, ligament, fascia, adipose, and skin are subjected to relatively low loads so that only elastic deformation occurs, then once that load is removed, the tissue will return back to its original shape and will be able to be loaded and unloaded thousands of times a day and still remain healthy and uninjured. However, if a large loading force is suddenly applied, greatly increasing tissue stress and causing plastic deformation (e.g., partial or complete tearing of ligaments, tendons, and fascia and fracture of bone), then that tissue will structurally deform upon application of the high-stress loading force, will not return back to its original pre-load shape and, by definition, that tissue will undergo injury.

By gaining a better appreciation of the load-deformation characteristics of our bodily tissues, including concepts of stress and strain, stiffness and compliance, and elastic and plastic deformation, the clinician will better understand how and why injuries occur within the foot and lower extremity. Even more important, these principles will also help in the design of optimal treatments for these injuries so that our patients will be able to perform their desired daily weightbearing activities with a minimum of pain and disability.

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