Essentials of Biomechanics

Principles of gait: The Initial Contact of Walking

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INTRODUCTION

In previous Essentials of Biomechanics, impulses (changes in force over time) have been discussed in regard to their appearance on force-time curves and how they relate to the management of energy. Last issue the inverted pendulum model of gait was explored as a method to transfer body weight over the foot during midstance. Impulses go up and down quite distinctly throughout walking gait to form a crude 'M'-shaped curve, something absent from running impulses. This is because running involves quite different force management to achieve locomotion. However, despite this difference in impulse generation between walking and running, a consistent theme in all initial contacts is the ability to apply deceleration braking to the fall of body weight (centre of mass – CoM). This braking period extends into loading response, not only to create deceleration of the CoM, but also as a mechanism of energy dissipation that moderates energies from the collision between lower limb and the ground that could cause tissue damage. Energy derived from an impact with the ground could be stored for use via elastic recoil latter. However, if energy is too high to safely store it all, then it is must be managed through dissipation, commonly referred to as shock absorption or shock attenuation.

The Problem of Human Bipedalism in Collision Events

Quadrupeds have four legs that can dissipate impact together, or more usually, in sequence. Other mammalian bipeds are hoppers that use both limbs as energy dissipaters at every bounce on very flexed hips and knees. In the case of kangaroos and wallabies, their strong tails and spines are also great elastic-tensile energy dissipaters. Only large terrestrial birds experience anything like human walking impulses, and they also developing an 'M'-shaped fore-time curve on a force plate when walking (Usherwood et al, 2012), but this lacks the initial impulse transient caused by a heel strike **(Fig. 1).**

Unlike humans, terrestrial birds shock-absorb via tendons attached to large muscles placed proximally around their very flexed hip and knee. Humans use very extended limbs, keeping them functionally long. This is perfect for using the limbs as an inverted pendulum to move the CoM over the plantigrade foot at the ankle, as longer limbs improve inverted pendulum mechanical efficiency in walking bipedalism (Usherwood et al, 2012). However, human gait style requires large muscle masses to be placed distally on the leg (calf), something not seen in other animals. Unlike walking, humans generate high-energy costs during running because of higher energy dissipation requirements (Griffin et al, 2003; Biewener et al, 2004). Running will be considered in more detail in further editions of Podiatry Review.

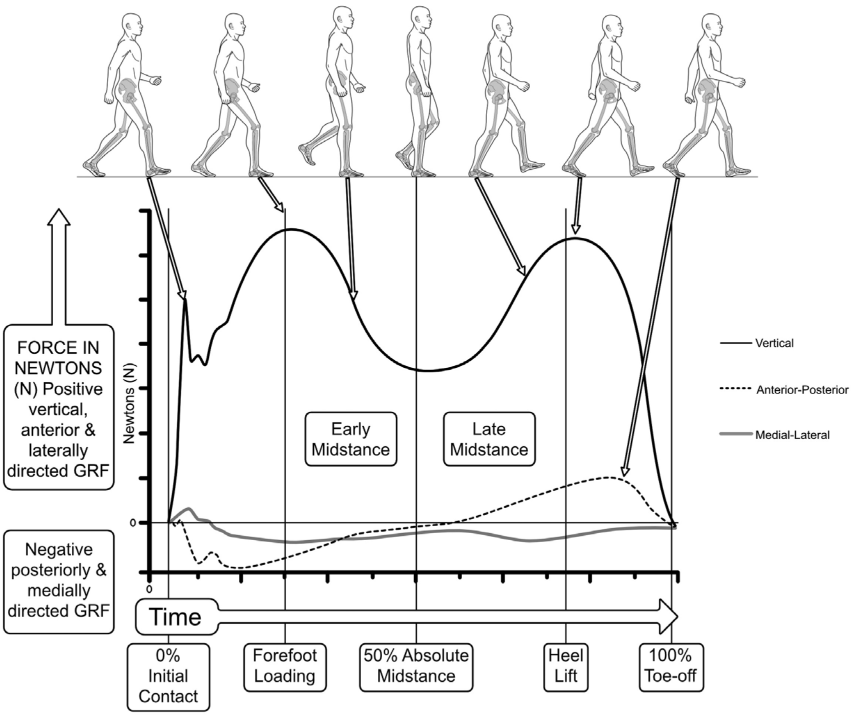


Figure 1
The force-time curve of human walking produces a sequence of rising and falling impulses that creates a crude 'M-shaped' curve. The braking phase of human walking involves an initial heel strike impulse, separate from the forefoot contact collision. This divides impact forces into two collision that spread shock-attenuation and lowers peak forces. Image with permission of www.healthystep.co.uk.

The Primary Human Shock Absorbers

Heel strike and forefoot contact separates impact into two collision events, reducing the peak energies needing dissipation by spreading them out (Ruina et al, 2005). Forefoot running creates a single impact event and quite different braking events around the ankle to a heel strike, and thus will be discussed in further editions of Podiatry Review. However, impacts in all foot contact positions and gait styles, set up large flexion motions across the knee and hip joints. Flexion moments cause eccentric contraction of extensor muscles to act as primary impact shock absorbers, forcing them to lengthen as they contract to dissipate impact energy (Roberts and Konow, 2013). This is achieved by a technique known as *muscle-tendon buffering.* On loading, tendon fibres lengthen first via their intrinsic elastic nature. Then, as the energy from tendon stretch is released under elastic recoil, the muscle fibres start lengthening (Roberts and Konow, 2013). Thus, the elastic recoil tendon shortening energy is lost, and therefore dissipated from motion during the increasing lengthening of the muscle fibres. The bigger the mass and cross-sectional area of any muscle and tendon, the better the energy dissipation can be. In humans, gluteus maximus and the quadriceps muscles (via the large patella ligament or tendon, for it is a hybrid like connective tissue structure) are ideal for shock attenuation at the hip and knee respectively **(Fig. 2)**

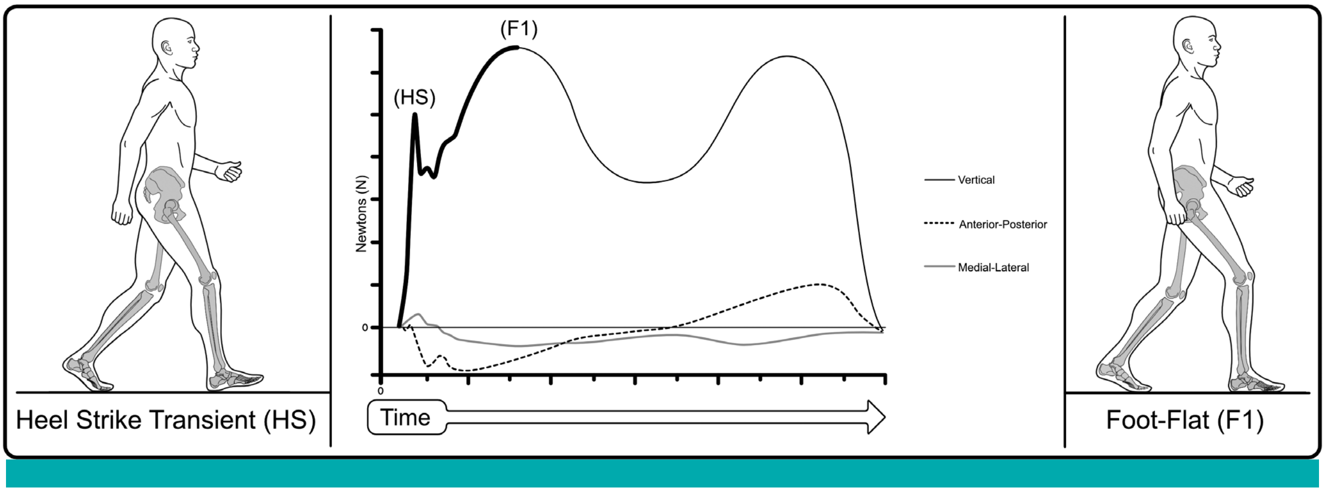
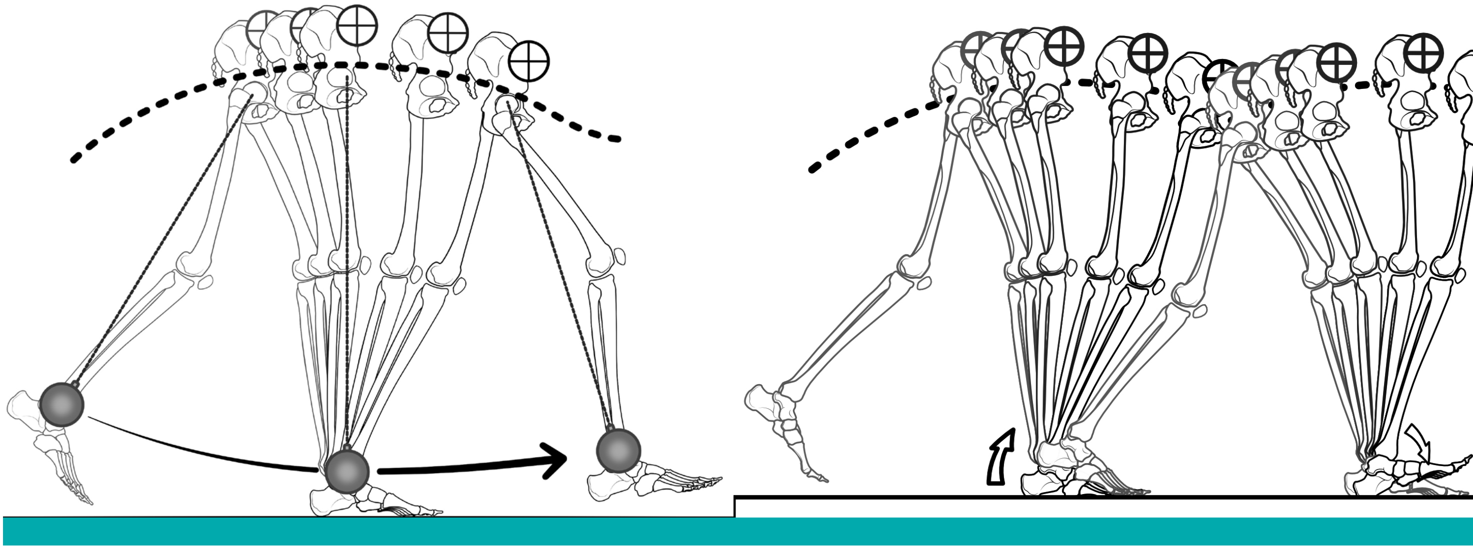


Figure 2
Large joint flexion angles increase from heel strike (HS) to allow muscle-tendon buffering via eccentric muscle contraction from impact to the end of loading response (F1 impulse peak). Thus, at the heel strike transient the hip continues to flex as it was doing in late swing, but with the knee and ankle also starting cycles of flexion. Gluteus maximus is primarily responsible for energy muscle-tendon buffering at the hip resisting hip flexion, while the quadriceps do the same at the knee. With a heel strike, tibialis anterior decelerates ankle plantarflexion, reducing the velocity of forefoot contact while also providing muscle-tendon buffering. Image with permission: www.healthystep.co.uk

In late swing phase, the swing limb is accelerating in a pendulum like manner via extensor activity at the hip (iliopsoas and rectus femoris) and the knee (quadriceps muscles). This sets up centrifugal forces that's pulls the body's CoM over the stance limb. As the swing limb enters terminal swing, the stance foot's heel lifts off the ground as a result of decreasing forces on the heel from the CoM being pulled forward by swing's centrifugal force. This allows energy in the Achilles to release its elastic recoil to 'spring' the heel off the ground, tipping up the stance limb to add extra momentum to the CoM. Heel lift increases the velocity of the swing limb's ~1cm fall into the ground (Ruina et al, 2005). The result is a significant, yet controlled collision between the swing foot and ground. Such collision energies are too high to just allow them to cause a shock wave throughout the body tissues. Collision energy needs to be managed, requiring flexion of the hip and knee immediately to provide some compliance, turning the lower limb into something like a shock-absorber spring.



In walking, the rearfoot (usually) makes first contact. The rearfoot is not a very mobile structure, save the ankle can provide significant sagittal plane motions of flexion and extension, plus a little eversion motion can be derived from the subtalar-ankle joint complex. Yet these joint shock-absorbing mechanisms are not providing enough energy dissipation at heel contact. The specialised tissue of the heel fat pad is needed to protect the rearfoot from heel impact by its elastic deformation.

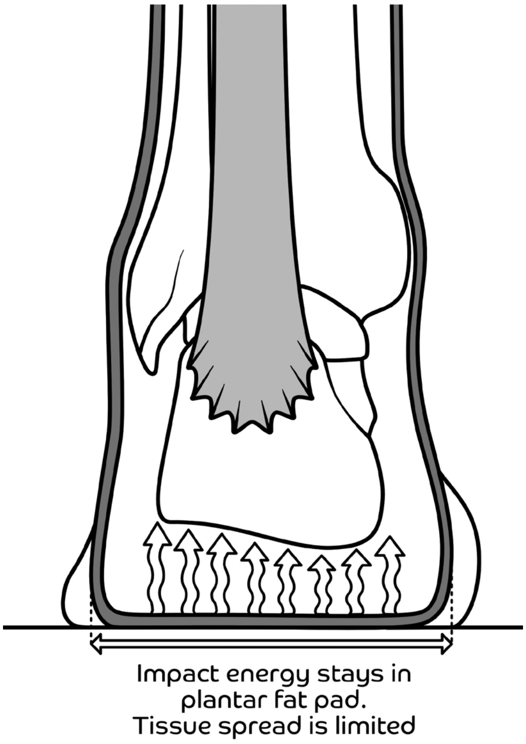


Figure 4
The rearfoot is relatively rigid and thus a poor shock absorber. During heel strike impact energies are primarily absorbed by the heel fat pad. With its fat cells enclosed in chambers walled by elastic connective tissue, the fat pad deforms compressing the fat and stretching the elastic chamber walls as it loads. On offloading, the elastic walls recoil back into shape, but the kinetic energy it removes from gait can not used for locomotion. Thus, the structure dissipates energy to protect deeper rearfoot anatomy such as the articular surfaces of the ankle and subtalar joints. Image with permission of www.healthystep.co.uk.

Figure 3
Swing phase should be a fundamental part of contralateral heel raise, for in late terminal stance the centrifugal forces 'pull' the CoM of the body forward, reducing the forces on the heel. Once these forces are lower than forces stored within the Achilles during late midstance from triceps surae activity, the heel will spring off the ground. Heel lift adds momentum to the CoM and tips the swing limb into collision with the ground. Image with permission of www.healthystep.co.uk.

By separating the foot contact into two events, the peak forces of each event are lower than the peak force of a single impact collision. With the initial ground reaction force (GRF) during heel strike behind the ankle joint, the ankle is forced to plantarflex (a flexion motion). Now the ankle can start to dissipate energy through the ankle extensor muscles (mainly tibialis anterior) before the forefoot collides with the ground at forefoot loading (foot flat). The ankle extensor muscle's energy dissipation is aided by tibialis posterior and peroneus longus that are actively tensing the foot (Kokubo et al, 2012). The ankle extensors also activate the windlass mechanism though digital extension, tensing the plantar aponeurosis (Flanigan et al, 2007; Caravaggi et al, 2009; Wager and Challis, 2016). Together, these events stiffen and raise the vault (arches) of the foot. This means as the forefoot strikes the ground, foot vault stiffness can be relaxed so that initial vault flattening can help dissipate impact through the concepts of strain deformation. The active muscles provide the muscle-tendon buffering as they relax. Thus, the foot demonstrates a period of stiffening before forefoot contact and then it offers compliance as the forefoot impacts the ground.

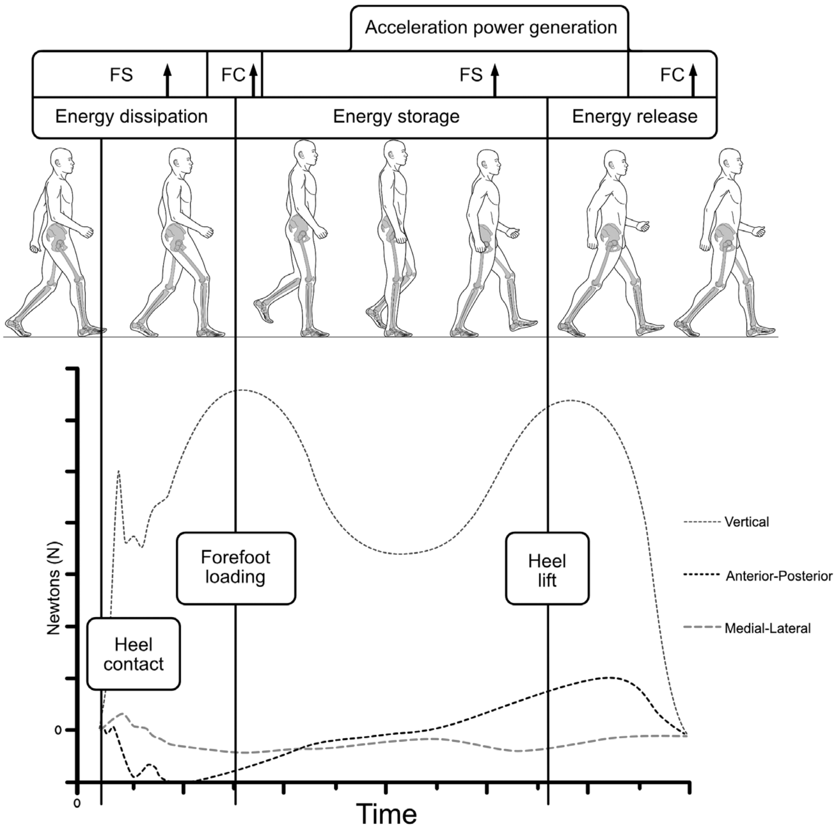


Figure 5
The foot's cycles of increasing foot stiffness (FS) and increasing compliance (FC). Note how foot stiffness is raised before forefoot contact during the heel strike transient impulse peak ready for forefoot loading, when foot energy dissipation is required via permitting increased compliance. For acceleration, the foot must be stiffened again to provide a semi-rigid lever. Image with permission of www.healthystep.co.uk.

The last major shock absorbing technique for humans is via soft tissue oscillations (Pain and Challis, 2006, Schmitt and Günther, 2011; Khassetarash et al, 2015; Riddick and Kuo, 2016). Collisions cause shock waves, which at the right frequency will cause an object to vibrate. Consider the striking of a tuning fork, where a 128 Hz tuning fork vibrates under impact amplitude that creates impact frequencies within that range.

Provide too gentle a knock on the tuning fork, and you won't hear it vibrate. Human collision impact frequencies are in the range that causes soft tissues to vibrate. The larger the muscle mass, the more it oscillates and the more energy it can absorb as it moves out of and then back into position as a result of the impact shock wave. By having large muscle masses in the calf, as well as anterior and posterior thigh and buttocks, humans provide both distal and proximal soft tissue vibrating energy dampers. This is important for an animal that impacts the ground with very extended limbs, with more energy absorbed by horizontal than vertical soft tissue motion (Schmitt and Günther, 2011).

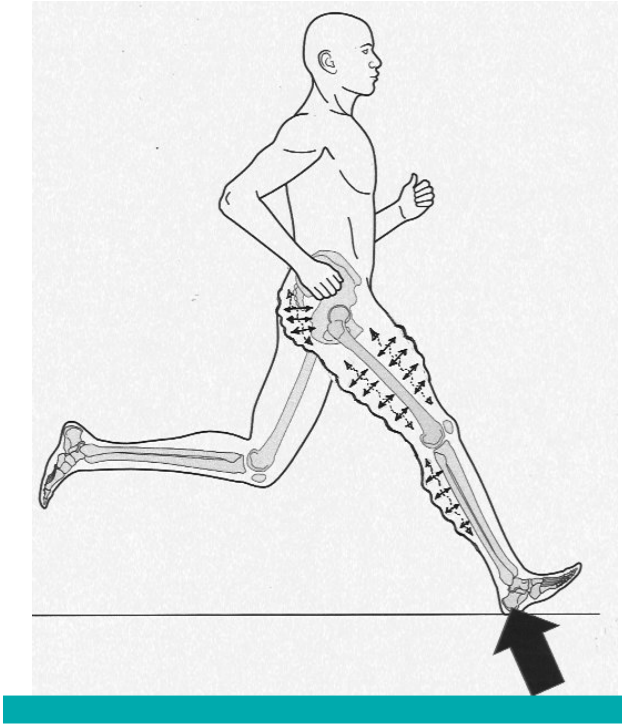


Figure 6
Soft tissue motions within the lower limb are important to the transmission and damping of impact energy, more so in running that walking, for human impact forces are larger at higher accelerations. Yet they are still at work, even in slow walking. Oscillations of large muscle masses as a result of the impact shock wave cause the restraining connective tissues to stretch and recoil, providing energy dissipation as they do so, particularly within horizontal plane motion. Image with permission of www.healthystep.co.uk.

Why is Shock Absorption Important to Human Gait?

Most large animals impact on very flexed joints, stretching the tendons but with muscles largely not changing their lengths any great distance. The limb's joint angles are then changed so that as the tendons spring back, with the 'bounce off' elastic recoil accelerating them forward. Human walking involves a distinct braking phase, followed by a separate weight transfer stage, and then followed by a separate acceleration phase. It is not a 'bounce down followed by bounce off' form of locomotion.

Phase one is a collision on a limb in front of the body, requiring dissipation of impact energies and a braking of acceleration of the fall of the body's CoM while maintaining its horizontal velocity. The highly efficient inverted pendulum action of midstance's weight transfer (see last issue), can then occur after the safe placement of the limb to the ground without any further high-energy dissipation being required. This technique is superb for energy efficiency, but with long limbs that utilise a high-positioned trunk posture where large joint flexions must be avoided, more ingenious mechanisms of initial shock absorption must be used to protect tissues at contact collisions.

Summary

The energy derived from an accelerated impact with the ground can be stored or dissipated. If energy is too high to safely store it all, then it must be managed through appropriate dissipation. Human walking involves keeping lower limbs away from high flexion angles to utilise the mechanical advantages of an inverted pendulum-like gait. This means the primary mechanism of energy dissipation of muscle-tendon buffering using large changes in flexion angles at joints is not desirable. Despite this, muscle-tendon buffering at the knee remains the primary shock absorber, with secondary actions from the hip and ankle. To assist dissipation mechanics, human walking uses a peak force reducing double foot collision of heel strike followed by a forefoot strike. The rearfoot is relatively rigid, so its impact uses the highly specialised heel plantar fat pad. The forefoot collision uses pre-tensioning of the foot vault as well as plantar fat padding, allowing the foot to relax, deform, and absorb energy at its contact. Finally, oscillations of soft tissue masses resulting from the impact shock wave can displace and then spring back into position, dissipating energy in connective tissue stretch and recoil.

In the next issue we will consider how the foot stiffens for acceleration.

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