The Biomechanics of Running

Understanding the many variables can help prevent or treat injuries.

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Walking and running, similar in so far as they are bi-pedal activities, are quite distinct from a biomechanical perspective. As a profession we spend much of our time evaluating normal walking gait and detailed studies and research have been conducted in this arena, but bio-mechanists have also studied running extensively. This article will look at some of the ways in which running is unique and should be considered separately.

The Gait Cycle

When walking, one foot is always in contact with the ground, and for a significant portion of the full cycle, some part of both feet are on the ground. This is known as double stance. In Inman's diagrams of ambulation,[1] gait is sometimes represented as two legs of a divider-compass swiveling forward, the body wobbling between points of near equilibrium. More recent models liken walking to the action of an inverted pendulum, with the body moving over a fixed foot, somewhat like the motion of a metronome.

Running, by definition, begins when there is some period of no ground contact. Float is the term used to describe the time when neither foot is touching the ground (some texts refer to this as "double float") and stance phase is then less than 50% of the overall cycle. There are two periods of float, when both limbs are off the ground, and there is no time when both feet are on the ground simultaneously. The faster the speed, the shorter the stance phase and the more time the runner spends airborne.

Initial contact occurs when the forward foot makes contact with the ground. Based on running style and speed, the hindfoot, midfoot or forefoot may strike first. In preparation for this contact, the center of mass has been falling and the body decelerating. Through this Absorption (braking) period, the knee and ankle flex to dissipate energy and store it in muscles and tendons. While still in stance phase, a clear reversal occurs as the body prepares for propulsion. Stance phase Generation is marked by the ankle, knee, and hip extending, with the leg muscles and tendons returning some of the previously stored energy. The center of mass moves upward and forward in preparation for toe-off (Figure 1).

Muscle-Tendon Elasticity

Studies conducted on the metabolic cost of running revealed that the consumption of energy was lower than predicted. It became clear that bodies do not move simply due to muscular activity. Both in walking and running, we are not just pushing ourselves forward. With this insight, researchers began to investigate and understand the mechanisms that lead to efficient running. From animal studies, scientists understood that both muscles and tendons have elastic properties that allow them to temporarily store energy. The body uses gravity during absorption to load the muscle-tendon storage springs, and then returns this energy in the second half of stance in preparation for toe-off.

EMG plots of muscle activity show that muscles fire in anticipation of

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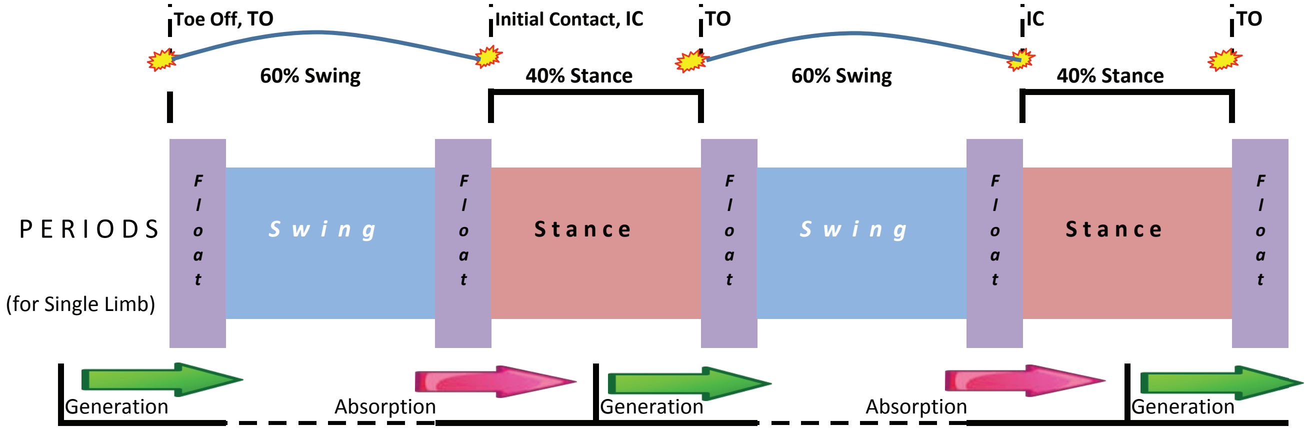

Figure 1: Stance is always less than 50% of the overall cycle and may be close to 20% for trained sprinters. Two periods of float—where the runner is airborne—occur in each cycle. A clear reversal of energy from Absorption to Generation takes place in midstance.

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initial contact so they can act as tensioners for the tendons. This is also known as the stretch-shortening cycle where muscles work eccentrically prior to concentric activity. During the absorption phase, the muscles act eccentrically as the tendons stretch. Later, during generation, the muscles contract and the tendons recoil. Both the higher step cadence of running and the deforming force of gravity allow for the efficient temporary storage of elastic energy that is re-used for propulsion. Elasticity of ligaments in the arch of the foot also contribute to this phenomenon. It appears that these mechanisms save approximately 50% of the energy that would otherwise be required.

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Stride Length and Frequency

In general, both stride length (distance, m) and stride frequency (strides per second, Hz) increase as speed increases. Short of sprinting, at a given running speed, most individuals choose both their stride length and stride frequency to minimize metabolic energy cost. Many variables will determine the right combination of these two—including speed, gradient, running surface, plus body dimensions and proportions. Runners tested over a range of velocities (3m/sec to 4m/sec—an increase of 33%) on average increased their stride length by 28%, while stride frequency increased by only 4%. This indicates that most runners have a fairly narrow band of preferred stride frequency when distance running.

It has been proposed that this characteristic preferred stride frequency is chosen subconsciously as the most economical for an individual runner. However, the period from initial contact up to midstance acts as a brake on the runner, retarding momentum. Several well-known running techniques, including The Pose Method and Chi Running, advocate a faster stride to minimize braking and capitalize on the energy return effect. Underscoring this, a recent study demonstrated that trained runners had a higher step rate and shorter step length than untrained runners moving at the same speed.[2] The trained runners were also about 7% more efficient. It would appear that by optimizing stride frequency, running performance can be improved for some individuals.

Arm Swing

In normal walking, arm swing plays a part in maintaining a balanced and efficient gait. Researchers developed the concept of counter-rotation to explain how arm and upper body swing works opposite leg swing. In walking, arm swing helps to reduce vertical oscillations of the center of mass, whereas in running, it actually contributes to vertical motion. By isolating the center of mass of the arms from the rest of the body, it is seen that they play a role in providing lift and, since running involves an airborne phase, this contribution to lift is very helpful. As speed increases, arm swing becomes more important and arm motion becomes more vigorous and animated.

The pattern of movement of the arms is opposite that of the legs and this assists in smoothing out changes in total body momentum. As the right leg comes forward through swing, the left arm also moves forward. This synchronous motion of opposing limbs is essential to keep the body's center of mass moving smoothly in a forward direction. Although right and left arm motions cancel themselves out in the forward direction (sagittal plane), this is not the case when considered through the vertical axis (transverse plane). Seen from above, with the left

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arm coming forwards and the right arm going backwards, they are actually both contributing to the same angular momentum.

In this example, the whole upper body is twisting in the clockwise direction. This occurs as the lower body is rotating in a counter-clockwise direction. The contribution of the arms and upper trunk nearly cancel out that of the lower trunk and legs. This is a very neat solution to the fact that the runner spends portions of each step airborne. Without this cancelling of angular momentum, the leg in swing, during float, would tend to twist the entire body while it is in the air.

Potential and Kinetic Energy

Within the gait cycle, there is an interplay of potential and kinetic energies. In walking, potential energy is highest at midstance, while the kinetic energy is lowest. The potential and kinetic energies are out of phase, swapping off through each step. During running, the energies are in phase, working together to propel the body into float.

One of the subtle distinctions between walking and running is the relative height of the center of mass at midstance. In walking, the center of mass is highest at midstance, as the body “vaults” over the fixed leg. Conversely, in running, the center of mass is lowest at midstance as the body prepares to push itself forward. It is an interesting difference, highlighting the alternate uses of available energy.

Injuries

As runners only ever have one foot on the ground, that foot must mitigate the entire burden of the ground reaction forces for the duration of stance. Depending on speed, the averaged ground reaction force increases 50% to 70%, and the maximum impact peak can be 2.5–3.0 times body weight. Compounding the issue, as runners spend less time in stance, cycle time is shortened and the total number of steps is higher. In addition, a runner’s foot placement is closer to the midline of the body, and with a narrower base of support, the leg angle changes.

The resulting increase in tibial varum may require further pronation of the foot. Over longer distances, fatigue is also a consideration as muscle function may change. This accumulation of both higher forces and frequency is often a recipe for injury, and under such demanding conditions, even slight biomechanical abnormalities can be the cause of problems.

Originally, it was believed that most running injuries were the re-

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sult of high impact forces, particularly those generated at heel strike. Over time, it has become clearer that many injuries occur as a result of the forces being dissipated and generated throughout the entire period of stance. During the energy absorption phase, from initial contact to midstance, the transfer is from distal to proximal—up the kinetic chain.

Movements across the subtalar joint, ankle, knee, and the related muscle and tendon stretching allow for the transfer of energy and the eccentric loading of muscles. The impact of initial contact is not just at the heel; the effect is borne along the entire leg, and occurs over a longer period. This sequence is then reversed in the second half of stance when muscles concentrically contract providing propulsion.

Despite a considerable amount of work on shoe design and running surfaces in the 1970s and 1980s to reduce impact forces, the rate of running injuries remained little changed. Studies of injury type and prevalence showed more proximal tissues were frequently involved. While runners often present with plantar fasciitis and Achilles tendinopathy, they also develop knee pain, iliotibial band syndrome, medial tibial stress syndrome and stress fractures, as well as hip and lower back pain (Figure 2).

It appears that these injuries result from stresses applied throughout the stance phase of running and not just impact. Accordingly, treatment needs to look at a host of factors beyond shock attenuation. For example, a mild undiagnosed leg length discrepancy of 1/4"+ may become a source of injury to a runner with increase in workout intensity. Likewise, other slight anomalies in muscle strength, functional length, or joint range of motion provide asymmetries that may become problematic under repetitive stress.

Studies show that the best predictors of movement-related injuries are sport-specific exposure, time, and previous injuries. Work by Benno M. Nigg, PhD, at the Human Performance Lab at the University of Calgary, and others indicate that during running, soft-tissue vibrations are short and heavily damped, independent of the shoe-surface combination.[3,4] It appears that the body's locomotor system minimizes the vibration of soft-tissue compartments automatically. Paradoxically, too much cushioning from a shoe or orthotic may inhibit this natural response.

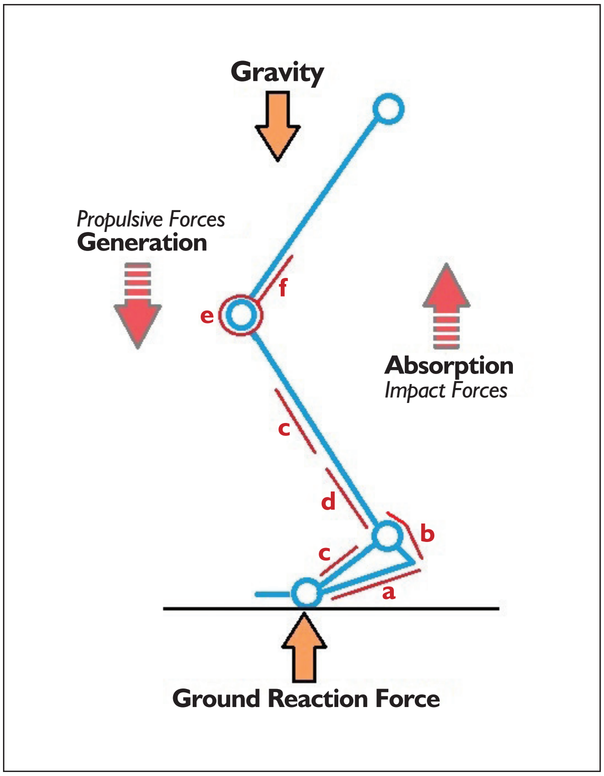

Figure 2: Common running injuries along the kinetic chain
a. Plantar heel pain
b. Achilles tendinopathy
c. Stress fractures
d. Medial tibial stress syndrome
e. Patellofemoral pain syndrome
f. Iliotibial band syndrome

Chronic injuries develop over time and can be long-lasting or constantly recurring. They account for the majority of running injuries. Many chronic exercise injuries have mild symptoms and low-grade pain, and as a consequence, they are often ignored or simply overlooked for months or years. Ignoring these signs can lead to a persistent injury that is difficult to heal and eventually result in breakdown.

When experienced runners develop a chronic injury, it is necessary to investigate what may have changed in their regimen. Dr. Stephen Pribut,[5] a member of the *Runner's World* Board of Advisors, cautions against the "terrible too's". These are common mistakes linked to over-training: too much, too soon, too fast, too often, and with too little rest. In light of this, training considerations become important in the evaluation and treatment of a patient (Table 1).

Foot Orthotics

Although the exact mechanisms of foot orthotic efficacy are still being researched, there is abundant evidence of their effectiveness in treating running injuries. Standard Root Theory prescribes functional foot orthotics with an emphasis on controlling rearfoot to forefoot position. This approach is valid in certain circumstances and especially where poor rearfoot control is considered the primary etiology of the presenting pain. However, in running, heel strike is a small percentage of overall stance, yet even after heel lift occurs, it remains important to control the foot. The peak and duration of the ground reaction force is larger in midstance, at the transition from absorption to generation, as the body accelerates for propulsion and float.

Under normal circumstances, pronation will reach a maximum at around 40% of the stance phase. In runners with excessive pronation, this will be delayed. Accordingly, many practitioners advocate midfoot and forefoot control in their sports orthotics. One metric to consider is navicular drop, the relative change in height of the arch. If the foot remains everted for too long—and external rotation of the tibia is delayed—it puts a strain on multiple joints and tissues. To address this, well-conforming orthotics can be constructed from semi-rigid thermoplastics, neoprenes or other resilient foams.

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It is also important to completely evaluate forefoot function, record areas of callusing, and verify range of motion, especially at the 1st MPJ. For maximum effect in athletes, forefoot posting should extend all the way to the sulcus. Longer and wider posts have a greater surface area to disperse forces through push off. For example, a mild functional hallux limitus resulting from a plantarflexed 1st metatarsal can be addressed with a reverse Morton's extension plus extended sulcus posting for the 2nd through 5th metatarsals. By altering the timing and duration of pronation and preventing the end range of motion, injuries can be successfully addressed or avoided.

Conclusion

Running is a fascinating choreograph of repetitive movement and transformation of energies—a wonderful, graceful co-ordination of body movement. Compared to walking, running is a complex activity with both higher forces and step rates. Slight anomalies in muscle or joint function can potentially become the source of injuries, and as such, the choices of running style, orthotics and shoes should be very much tailored to the individual. Their experience is far more important than any single prevailing theory. Careful evaluation and consideration of a runner's biomechanics and the proper selection of orthotics and shoes can be effective in preventing and treating injuries. This article serves as an introduction to a rich topic, an entry-way to further study and understanding.[6-9] **PM**

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TABLE 1:
Training Considerations

Many running injuries result from training errors and, broadly speaking, treatment will follow a protocol of pain relief, possibly rest, icing, stretching, focused strengthening and improvement of biomechanics. Good support from shoes and orthotics, good running form, and good training habits will help prevent the return of many of these injuries.

- Make changes in distance or tempo gradually.
- Break in new shoes slowly over a few runs. Ensure that the last and sole design complement the runner's foot type, i.e., pronator, supinator, or normal/neutral.
- It is recommended that runners switch out sneakers every 400-500 miles. If sneakers are over-worn, they lose shock absorption and their ability to control rearfoot and STJ motion.
- Avoid running on roads too often due to the unrelenting hard surface and the banked edges. Look for firm trails with some forgiveness such as dirt, woodchips, fields, or boardwalk. Slightly uneven terrain also helps avoid a 100% exact repetition of each stride.
- Changes in running technique should be applied slowly to allow the body to adapt.
- Changes in weight and aging can also be contributing factors to the onset of an injury. •

References

1 Inman, Ralston, Todd, Human Walking, Williams & Wilkins, 1981.

2 Gómez-Molina, Josué; Ogueta-Alday, Ana; Stickley, Christopher, et al. Differences in spatio-temporal parameters between trained runners and untrained participants, Journal of Strength & Conditioning Research (Post Acceptance: October 06, 2016).

3 Nigg, Benno, PhD,Biomechanics of Sport Shoes, Co-director of the Human Performance Lab University of Calgary, Alberta, Canada 2010.

4 Kennedy, Seamus B, Exploring a New Paradigm in Biomechanics, The O & P Edge, Nov 2011.

5 Pribut, Stephen The Top 5 Running Injuries Seen in the Office, Parts 1 & 2. Podiatry Management April and June 2013.

6 Cavanagh, Peter R. (Editor)Biomechanics of Distance Running. Human Kinetics Books, 1990.

7 Novacheck, Tom F., The Biomechanics of Running, Review Paper. Gait & Posture, 1997.

8 Nicola Terry L., Jewison, David J., The Anatomy and Biomechanics of Running. Clinics in Sports Medicine, April 2012.

9 Burnfield, Perry, Gait Analysis, Normal and Pathological Function. (2nd Ed, Chap 18) Slack, 2010.

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