CHAPTER 4

HOW TO DEVELOP THE IDEAL RUNNING FORM FOR ENDURANCE, SPRINTING, AND/OR INJURY PREVENTION

From a biomechanical perspective, it makes sense that nearly every runner has some slight anatomical imperfection that can detract from optimal performance. Think of how automakers have to blow streams of smoke over a car's exterior in a wind tunnel to identify subtle design flaws that could affect gas mileage and/or speed. In regard to running, by far the most common factor that can result in less than optimal performance is prior injury. A perfect example of this is how a damaged Achilles tendon fails to store and return free energy, thereby significantly decreasing efficiency. Muscle weakness is also notorious for causing problems with performance. This is especially true for weakness of the external hip rotators, which may allow the entire lower extremity to rotate inward too far. This inward rotation not only detracts from performance but also greatly increases the risk of injury.

It's not just prior injuries that can create problems. The routine use of heavy motion control sneakers reduces the range that your toes bend during push-off, gradually weakening the intrinsic muscles of the arch. Arch weakness correlates with the development of plantar fasciitis and impaired athletic performance, particularly as we age. Given the potential for creating movement patterns associated with less than optimal performance, it's essential you identify each and every risk factor potentially affecting performance.

Assuming you've read Chapters 1–3 and you're working on correcting your specific biomechanical glitches, the next step is to develop the ideal running form to maximize efficiency and reduce your overall risk of injury. The specific running form you choose depends upon how fast you plan on running. Because the running form of sprinters is different to that of endurance runners, which in turn is different to that of recreational runners, you'll need to select the running form that matches your desired speed. For example, the world's fastest sprinters require larger ranges of hip motion than distance runners in order to achieve the 16-foot stride lengths necessary for top performance. The neuromotor coordination necessary to attain a sprinting cadence of 250 foot strikes per minute is nearly unimaginable and needs to be addressed with specific running drills. Conversely, elite marathon runners require less overall mobility than sprinters, but their tendons need to be extremely resilient to store and return the free energy needed to run 26.2 miles at a sub-five-minute mile pace. Over the course of a marathon, elite runners must absorb and attempt to return over 6,500 tons of impact force, and so they need to focus on maximizing their shock absorption systems. Finally, the movement patterns of elite sprinters and distance runners are very different from those of slower recreational runners, who have stride lengths of about 5 feet (1.5 m), cadences of 150 foot strikes per minute, and often avoid the airborne phase of running altogether by ground running with one foot or the other constantly on the ground. Avoiding an airborne phase won't allow you to run fast, but it will greatly decrease your risk of injury.

The following section reviews the biomechanical differences between elite long-distance runners and sprinters, and applies this information to ways in which you can improve performance and efficiency yourself. The chapter concludes by explaining how to perform a detailed video gait analysis, with recommendations for visual and auditory gait retraining. Lastly, you will find a list of specific exercises and agility drills that can help you run faster and more efficiently regardless of your running level.

THE MAKING OF A GREAT ENDURANCE RUNNER

According to the exercise physiologist Tim Anderson (1), the best male long-distance runners tend to be slightly shorter than average, while females tend to be slightly taller than average. Male or female, the best long-distance runners possess muscular hips, thin legs, and small feet. Distance runners with muscular hips and relatively thin lower legs are more efficient because accelerating and decelerating heavy legs contributes greatly to the metabolic cost of locomotion. Since the feet and legs have long levers to the hips, even a slight increase in weight applied to the foot will greatly reduce efficiency. To prove this, researchers measured oxygen consumption before and after adding weights to either the foot or thigh of recreational runners, and determined that while adding weight to the thighs had little effect on efficiency, the same weight added to the feet more than doubled the metabolic costs of locomotion. Other studies have confirmed that every 100 grams (3.5 oz.) of weight you add to a running shoe increases the metabolic cost of running by 1%. These findings explain why endurance runners with small feet are more efficient than their large-footed rivals (2).

One of the most important factors that separates the world's best distance runners from their less successful peers is that successful distance runners plantar flex their ankles 10° less during propulsion, and this reduced movement occurs at a faster velocity (Fig. 4.1) (3, 4). The decreased range and increased speed of ankle plantar flexion

Fig. 4.1. *The best runners plantar flex their ankles more rapidly, through a smaller range of motion.*

is most likely the result of the Achilles tendon rapidly snapping back during early propulsion when it shortens to return stored energy.

In a paper published in the *European Journal of Applied Physiology*, world-class Kenyan endurance runners were found to have longer Achilles tendons that more effectively stored and returned energy compared to height-matched control subjects (5). According to the authors, the longer, more resilient, Achilles tendons present in the Kenyan runners were “optimized to favor efficient storage and recoil of elastic energy.” The only flaw with this paper is that the authors compared world-class Kenyans to non-world-class controls. It is likely that all world-class endurance runners have longer, more resilient, Achilles tendons compared to controls. As mentioned in the previous chapter, you can improve the ability of your Achilles tendon to store and return energy by performing isometric contractions with the tendon maintained in a lengthened position. While you can’t make your Achilles tendon longer, you can easily make it more resilient.

In an interesting study of efficiency in middle- and long-distance runners competing in a 5K race, researchers from Japan determined that the center of mass in the best runners moved with a vertical displacement of only 2½ inches (6 cm), while the less efficient runners averaged vertical displacements of 4 inches (10 cm) (6). The authors also noted that the good runners ran 5K in 2,825 steps, while the poor runners required 3,125 steps. The added work associated with lifting the center of mass the additional 1½ inches (4 cm) with each stride produced an increased workload roughly the equivalent to the cost of running up a 50-story building.

In what is without doubt the most thorough paper on running economy and performance to date, researchers from the United Kingdom evaluated 97 experienced distance runners (47 females) to determine exactly which biomechanical factors were associated with improved running economy and which factors were related to performance (7). To evaluate economy, the authors analyzed a range of respiratory gases and the velocity of lactate turn point (a marker of fatigue). The correlation between running performance and running form was determined by measuring three-dimensional motion of the spine, pelvis, and lower extremity during all phases of gait, and then analyzing which specific movement patterns correlated with each runner’s season’s best running time. The authors looked at stride length normalized to height, cadence, vertical oscillation of the pelvis, braking forces, posture, and the position of the hip, knee, and foot during different phases of the running cycle.

Surprisingly, even though all participants were experienced distance runners, including 29 elite runners, there were huge variations in all aspects of running form. For example, vertical oscillation of the pelvis varied twofold and braking forces differed by 280%. Cadence ranged from 144 to 222 foot strikes per minute, while stride length normalized to height was between 1.04 and 1.49 times the runner’s height. Runners also showed significant differences in the positions of their feet, legs, and hips at touchdown. Some runners made initial ground contact with their foot plantar flexed 11°, while others hit the ground with their foot dorsiflexed 24°. The position of their lower legs varied from 1 to 16° relative to vertical, and the forward lean of the trunk varied by 20°.

After analyzing all the data, the authors found that the most economical runners had reduced vertical oscillation of the pelvis, lower braking force, stiffer knees, shorter stride lengths, and a more vertical leg during initial ground contact. Running performance was predicted by lower braking forces, a more vertical leg during contact, reduced spinal motion, and reduced ground contact times. The best part of this study was the conclusion that simply positioning your leg in a near vertical position at initial touchdown could improve both economy and performance. In fact, having a nearly vertical leg at touchdown explained 10% of a runner's performance, and this is one of the easiest changes in running form you can make. Fig. 4.2 summarizes the various joint interactions associated with improved performance and efficiency. The authors point out that their study provides "novel and robust evidence" that running form strongly influences running economy and performance.

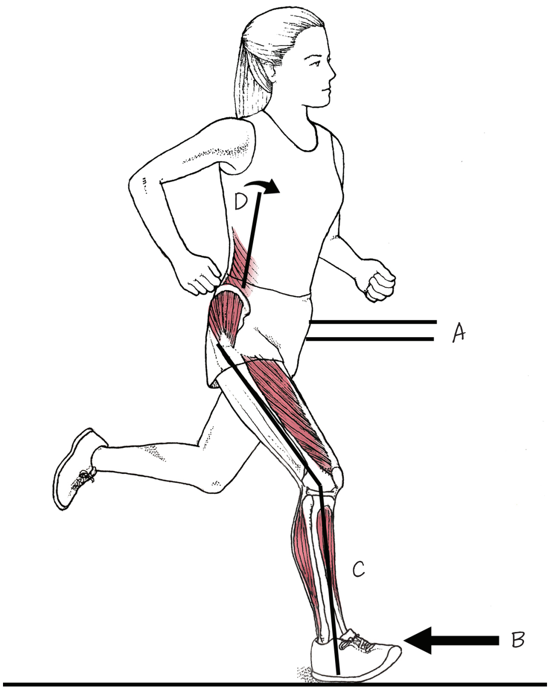


Fig. 4.2. ***Biomechanical measurements associated with improved performance and efficiency.*** *Folland et al. (7) proved that the most economical runners presented with reduced vertical oscillation of the pelvis (**A**), lower braking forces (**B**), shorter stride lengths, and a more vertical leg during initial ground contact (**C**). Runners with the fastest running times presented with decreased braking forces, shorter ground contact times, a more vertical leg at initial contact (**C**), and a reduced range of spinal motion (**D**). Reduced vertical oscillation of the pelvis and a more vertical leg at touchdown most strongly correlated with both improved economy and faster running times.*

FACTORS RESPONSIBLE FOR SUCCESSFUL SPRINTING

In a classic study published in the *Journal of Applied Physiology*, Peter Weyand and colleagues proved that the fastest sprinters spend less time on the ground and generate significantly more force while they are making ground contact (8). Interestingly, fast and slow sprinters spend about the same amount of time in the air and reposition their swinging limbs at about the same rate. These authors demonstrate that increasing the force applied to the ground by $^1/_{10}$ body weight will increase the top speed of running by 1 m/s. While stride length increases significantly with faster running, each runner has an upper limit to the length of his/her stride, after which continued increases will actually lessen speed. For the 30 sprinters in their study, stride length was maximized at 8 m/s (a 3:20 mile pace), while cadence gradually increased to the maximum speed of 9 m/s (3:00 mile pace). In all of the sprinters, the aerial phase of running continued to increase until the 4:30 mile pace, at which time it decreased slightly until the maximum sprint speed was achieved.

To understand stride mechanics, researchers from the United Kingdom (9) studied stride lengths in different sprinters and noted that some sprinters self-selected excessively long strides with low cadences, while others ran with short strides and high cadences. The authors suggest that the sprinters with the longest strides may have chosen long stride lengths because of an inability to rapidly turn their legs over. Conversely, the sprinters that self-selected high cadences may have done so because of an inability to lengthen their stride. These researchers propose that athletes who are overly reliant on long strides should do drills to increase their leg turnover (such as pool running with a high cadence), while athletes dependent upon high cadences should focus on improving flexibility and strength in order to achieve longer strides. By giving the athlete the option of increasing cadence and/or stride length, faster running times may be possible.

Anatomical studies have shown that sprinters have significantly longer muscle fibers in their gastrocnemius muscles compared with non-sprinters (10, 11). The longer fibers might allow these muscles to behave like large rubber bands that store and return energy more effectively than short fibers. The longer fibers can be inherited but more likely result from training, since muscles rapidly adapt to high-intensity training by increasing muscle fiber length. Research in 2006 showed that muscle fiber length can be increased by exercising muscles in their lengthened positions (12).

Unlike distance runners, sprinters flex their hips and knees through larger ranges during swing phase, and these motions occur at faster velocities. As a result, the trailing knee of the fastest sprinters is farther forward when the lead foot touches the ground (Fig. 4.3).

According to some experts, recovering the back leg more quickly allows sprinters to immediately pull the lead foot backward upon impact. Excessive knee flexion during swing phase is essential to sprint rapidly because flexion of the knee shortens the relative length

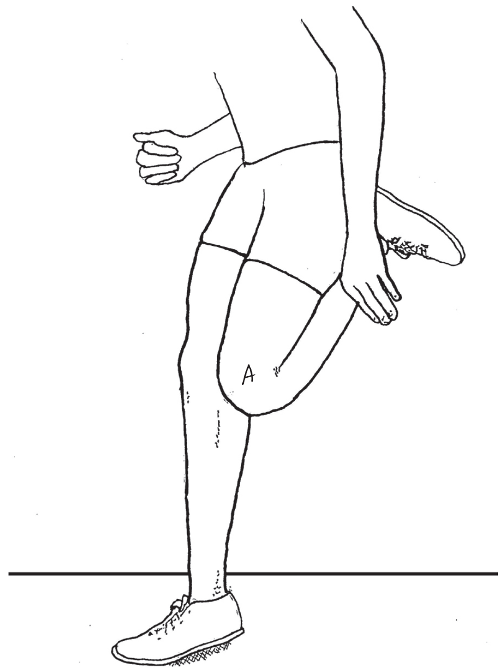


Fig. 4.3. ***The best sprinters flex their knees and hips through large ranges of motion, and the trail knee is farther forward (A) when the lead foot contacts the ground.***

of the lower extremity, which decreases muscular strain on the hip flexors (the lever arm to the hip is shorter when the knee is flexed). You can demonstrate this on yourself by placing an exercise band around your ankle and pulling forward: When your leg is straight you can feel the hip flexors strain, but when you bend your knee, there's a significant decrease in stress placed on the hip flexors. The world's fastest sprinters take advantage of the reduced lower extremity lever arm associated with knee flexion by pulling their heels up toward their hips as they pull their knees forward. Since marathon runners occasionally need to sprint toward the finish line, the best coaches suggest that endurance runners learn to move their hips and knees like sprinters. Watch a few slow-motion videos of elite marathon runners and you'll notice that during swing phase, the best

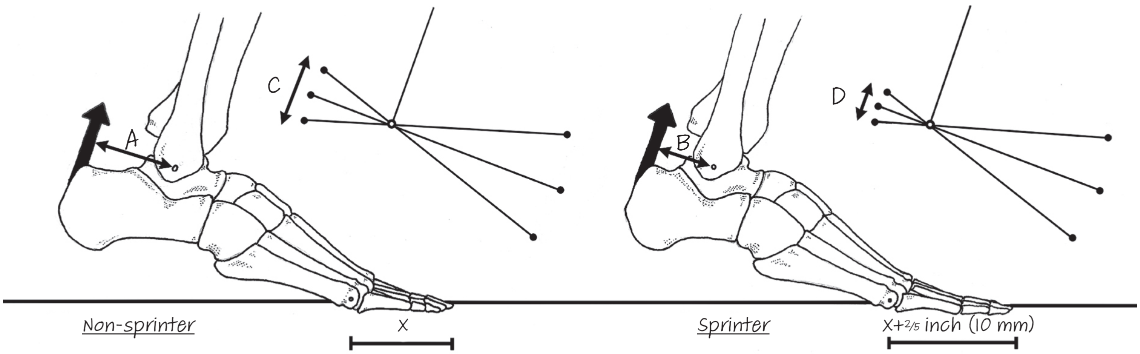


Fig. 4.4. ***Because the distance from the Achilles tendon is 25% longer in non-sprinters (compare A and B), the gastrocnemius and soleus muscles must move through larger ranges of motion to plantar flex the ankle (compare C and D).*** *Notice that the toes of sprinters are ⅖ inch (10 mm) longer than those of non-sprinters.*

elites move their hips and knees similarly to sprinters.

In an interesting study of foot shape in sprinters, Lee and Piazza (13) determined the distance from the back of the heel to the center of the ankle is 25% shorter in elite sprinters than in the non-sprinter controls. Conversely, sprinters possess toes that are almost ⅖ inch (10 mm) longer than the toes of the non-sprinter controls. While counterintuitive, the 25% shorter lever arm allows the Achilles to plantar flex the ankle effectively, with little change in length occurring in the gastrocnemius and soleus muscles (Fig. 4.4). The reduced lever arm may decrease mechanical efficiency of the Achilles tendon, but it allows the gastrocnemius and soleus muscles to move the ankle with a nearly isometric contraction.

On the opposite side of the fulcrum, the longer toes result in greater force production in the forefoot because the increased toe lengths provide the toe muscles with significantly longer lever arms that allow a more powerful push-off. Even though the added metabolic cost of accelerating and decelerating the longer, heavier toes would lessen efficiency while walking and running long distances (which is why evolution has favored shorter toe lengths), the longer toes provide increased force production during propulsion, thereby allowing the elite sprinter to run at the fastest speed possible. The combination of a short Achilles lever arm coupled with long toes is also found in nature; e.g., cheetahs, which are capable of sprint speeds exceeding 70 mph, have shorter heels and longer toes than lions. While you can't change your toe length, you can significantly improve sprinting speed by increasing toe strength.

THE BEST DRILLS AND EXERCISES FOR IMPROVED PERFORMANCE

Whether you're a sprinter, distance runner, or recreational runner trying to get faster, you should consider incorporating specific plyometric drills designed to improve the storage and return of energy. My favorite plyometric drills are illustrated in Fig. 4.5.

One particular study showed a 5% improvement in VO_2 and a 3% improvement in 3K race performance after just six weeks of plyometric training (14). The authors attributed the improved performance and speed to an

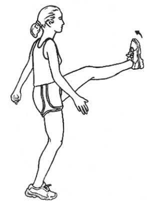
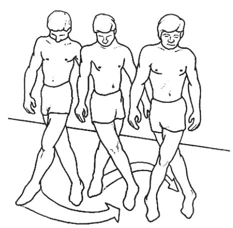
Glutes	While walking, lift knee toward chest, raising the body on the toes of the opposite leg.	
Hamstrings	Walk while swinging your leg forward until a stretch is felt in your hamstrings. Keep your toes pointing toward your knee.	
Adductors	While moving forward, raise the trail leg by abducting the hip 90°, while keeping the knee flexed. Move as though you were stepping over an object just below waist height.	
Gastrocnemius	Tip-toe walking. Move forward while alternating walking on your tiptoes. The aim is to raise your body as high as possible with each step.	
Quadriceps	Rapidly kick heels toward buttocks while moving forward.	
Abductors	Quickly move sideward alternating one leg in front of the other. Go 15 yards (13.5 m) and repeat in opposite direction.	

Fig. 4.5. ***Dynamic stretching drills.*** *(Modified from Turki et al. [15].)*

enhanced ability of the muscles and tendons to store and return energy following the completion of the plyometric drills. By increasing the speed of force production without increasing muscle size (large muscles consume more calories and are therefore less desirable for distance running), plyometric drills may allow athletes to spend less time on the ground while simultaneously producing greater force. Bounding drills that encourage rapid ankle plantar flexion during propulsion are especially helpful when trying to improve efficiency.

In another interesting paper (16), researchers from New Zealand had high-level distance runners perform a series of six ten-second strides while wearing a weighted vest (loaded with 20% of their body weight). A control group of runners performed the same running drills without the weighted vests. The researchers noted that shortly after performing the drills, the runners with the weighted vests had huge improvements in peak running speed and economy. Apparently, the weighted vests allowed for faster running times and improved efficiency because the runners were forced to stiffen their knees and hips in order to absorb the forces associated with carrying the added weight. The increase in leg stiffness resulted in big improvements in performance and economy because stiff muscles are more efficient at storing and returning energy. The improved form persisted even after the weights were no longer worn.

I really like that study, as the added weight allows your central nervous system to analyze impact forces at contact and modify limb position and stiffness accordingly. For example, if you had excessive up-and-down oscillation of the center of mass and/or were overstriding, you might not notice this if you're strong and healthy, but the amplified impact force associated with wearing the weighted vest would make it more obvious. My only concern is that the weighted vests used in this study were pretty heavy, which could increase the risk of injury. Less fit or inexperienced runners should definitely start out with lighter weights and gradually increase the load based on comfort. Runners who don't want to experiment with weighted vests can also increase their efficiency and performance with plyometric training and/or high-intensity uphill interval training. As with weighted vests, plyometrics and high-intensity training can increase the risk of injury so these drills should be initiated cautiously.

Lastly, because isometric contractions performed with muscles maintained in their lengthened positions have been proven to enhance tendon resiliency, I've outlined a few simple exercises that you can do in five minutes or less to keep your muscles and tendons strong and supple (Fig. 4.6). Whether you run a marathon in two hours or six hours, these exercises can help improve performance and reduce your risk of injury.

To improve resiliency in your glutes and quadriceps tendons, warm up with 25 lateral step-ups (Fig. 4.6, A). Next, move into a long-step forward lunge position and hold this position with your back knee held slightly off the ground (Fig. 4.6, B). This exercise places less stress on your knee than conventional lunges (17), and in addition to placing the glutes and quads in the forward leg in their lengthened positions, the rectus femoris in the back leg is isometrically tensed in a lengthened position. Maintain this position for 20 seconds and repeat four times. A resilient rectus femoris tendon is essential for fast running, as it snaps the trail leg forward to initiate swing phase.

Your Achilles and calf tendons can be made more resilient using the ToePro platform. Warm up by

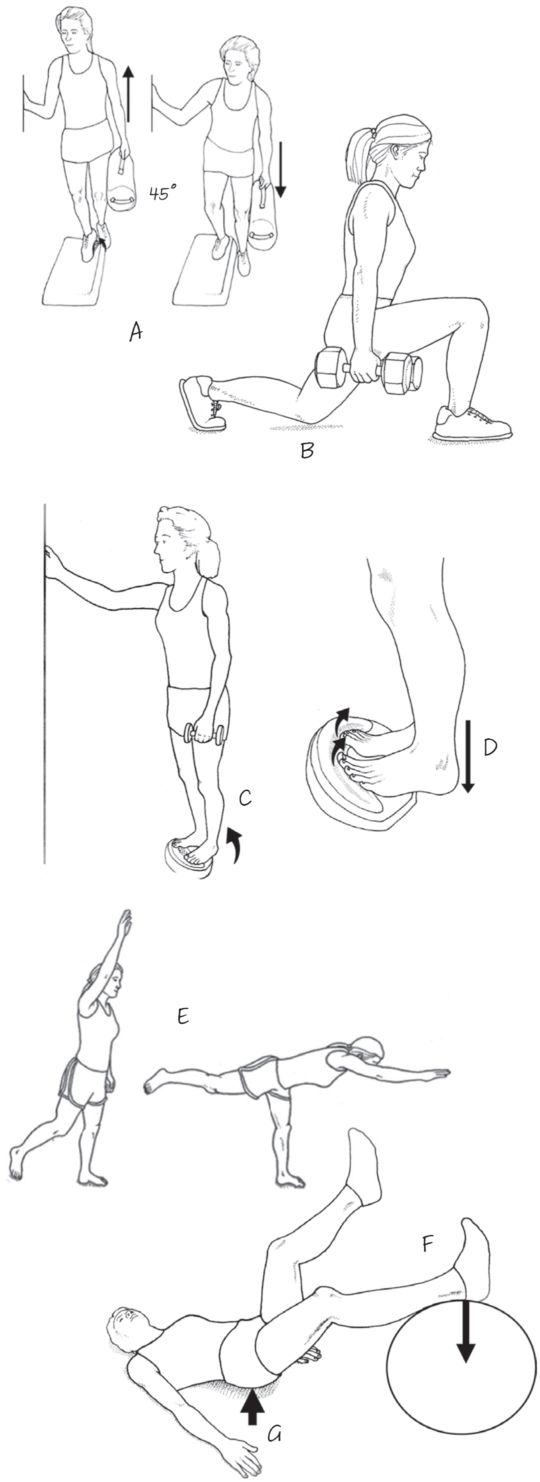


Fig. 4.6. ***The best exercises to improve tendon resiliency.***

doing 25 repetitions on the ToePro (Fig. 4.6, C) and then slowly lower your heels so they are ½" from the ground (Fig. 4.6, D). Hold this position isometrically for 20 seconds and repeat that routine four times. With each set, alternate between raising and lowering your arch to isolate different tendons: Your peroneals are lengthened when your weight is on the outside of your foot, while your tibialis posterior tendon is lengthened when your foot is rolled inward. If you don't want to use a ToePro, you can do this exercise by leaning forward into a wall while standing on an AIREX balance pad. With all of these exercises, you need to be fatigued when you finish, and so stronger runners may need to wear a weighted backpack or hold a dumbbell.

The most effective exercise to improve resilience in the glutes and hamstrings is the single-leg push-down. Before performing this exercise, warm up with a standing windmill exercise, illustrated in Fig. 4.6, E. After you're warmed up, lie face up on the floor with your arms out for stability, then place your foot on a physioball or workout bench and push-down with your heel (Fig. 4.6, F) with enough force to raise your pelvis off the ground (Fig. 4.6, G). Try to duplicate the position your hip is in during initial contact, which is typically between 20 and 30° of flexion. Hold this position for 20 seconds and repeat four times on each leg. If this exercise is too difficult, bring the opposite knee toward the chest. Conversely, if you're not fatigued after 20 seconds, straighten the opposite leg so it is closer to the leg that is pushing down, which makes the exercise significantly more difficult. This exercise duplicates the position your foot is in just before initial ground contact and markedly strengthens the hamstring tendons, which are important for both shock absorption and storing and returning energy.

MODIFY YOUR RUNNING FORM TO AVOID INJURY

Because the best predictor of future injury is prior injury, the most effective way to avoid future running injuries is to accommodate your prior running injuries. The easiest way to do this is to select either a heel or forefoot contact point depending upon your prior injuries. While studies comparing impact forces associated with different contact points consistently show that the same force is absorbed by your body, regardless of how your foot strikes the ground, it is possible to shift the location of the impact force simply by changing your contact position. If you have been plagued with chronic knee pain, transitioning to a forefoot strike pattern can reduce load on the back of your knee by 50%. Conversely, if you been struggling with plantar fascial or Achilles injuries, definitely consider switching to a lateral heel strike, as this will significantly reduce stress on the back of your calves and arches. The same is true for runners with a history of recurrent ankle sprains, since forefoot contact points increase the risk of inversion ankle sprains. As a general rule, midfoot and forefoot contact points tend to be more comfortable in runners with neutral arches and wide forefeet, while runners with low arches and narrow forefeet tend to prefer making ground contact along the outer heel.

If you have been dealing with an injured knee and you don't want to switch to a forefoot contact point, an alternate technique to offload your knee is to lean slightly farther forward at the hips during initial contact. This slight forward lean has been shown to redistribute pressure away from the knee and into the hamstrings (Fig. 4.7).

While not an option for fast runners, ground running is absolutely the easiest way to avoid ever being injured. The problem is, you have

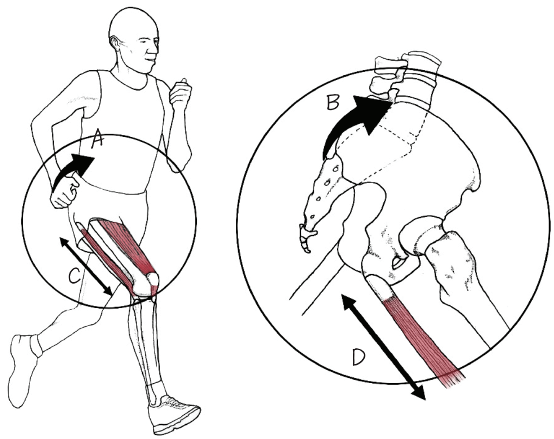


Fig. 4.7. ***By leaning slightly forward at the hips (arrows A and B), runners use their upper hamstring muscles (C and D) to absorb force that would normally be absorbed by the knee.*** *Some great research proves that the world's best runners make initial ground contact with their upper bodies tilted slightly forward, while less efficient runners contact the ground with their spines almost vertical (2).*

to run slower than a 13-minute mile pace. If you're a faster runner less concerned with performance and more concerned with staying healthy, the easiest way to avoid injury is to reduce your stride length. In addition to reducing impact forces, slight reductions in stride length cause you to strike the ground with your feet slightly farther apart. Researchers from Iowa State University (18) demonstrated in 2015 that reducing stride length by 5 to 10% caused runners to strike the ground with their feet almost ⅖ inch (10 mm) farther apart. The increased distance between their feet was accompanied by slight decreases in pelvic drop and reduced strain on the iliotibial band. Prior research has shown that increasing the distance between your feet while running may also be an effective way to decrease the risk of developing tibial stress fractures (19).

In an astute study of runners with patellofemoral pain, researchers from the United Kingdom had runners with chronic knee pain increase their cadence by 10% with the aid of an audible metronome (20). The training consisted of a single session of changing cadence to match the metronome and the outcomes were pretty impressive: Metronome training resulted in significantly less pelvic drop, decreased adduction of the thigh, and decreased knee flexion upon contacting the ground. These changes persisted when the runners were reevaluated three months later, and during that time, runners were able to increase their weekly mileage and reported significantly less knee pain. You can download any of a variety of running metronome apps from the iOS App Store for an iPhone or from Google Play for an Android device.

An important fact to remember is that because runners come in all shapes and sizes, there is no one form that is ideal for everyone and each runner should develop a style of running that suits his or her own specific biomechanical needs. A perfect example of this is how some people naturally run with a toe-out running form. While most running experts will tell you that runners should keep their feet straight and aligned, runners with external tibial torsion would be chronically injured if they ran with their feet pointing straight. Given the high impact forces associated with running and the nearly 90% annual injury rate, the best way to remain injury free is to accommodate your specific biomechanical alignment patterns, improve strength, flexibility, and endurance, and analyze your gait to identify subtle problems that might be increasing your risk of injury; e.g., excessive inward rotation of the hip, overstriding, excessive pelvic drop, and/or running with a crossover gait pattern.

PUTTING IT ALL TOGETHER: PERFORMING AN AT-HOME GAIT ANALYSIS

Although gait evaluation is complex and often requires the skilled eye of an expert, there are specific measurements that can be taken with an at-home gait analysis to help you improve performance and prevent injury. While it is usually possible to correct gait asymmetries with specific stretches, exercises, and/or gait retraining, runners with complex movement patterns should consider setting up a time with a local running expert, as there are many variables in neuromotor coordination and/or soft tissue contracture that are difficult to figure out on your own. For most runners, however, a thorough at-home gait evaluation can reveal obvious alignment problems that, when corrected, can make a huge difference in performance and in running longevity.

To perform your gait evaluation, find a treadmill that has enough space around it to place a camera in front, at the side, and behind while you're running. If possible, borrow a friend's camera or phone so you can capture all three angles at once. It's not necessary to use three cameras, but it makes the process quicker. Ideally, each camera should be mounted on a tripod, but you can also have a friend with a steady hand record the videos. The videos should capture your entire body from the back and side cameras, but you'll only need a view from the hips down for the front view. The front and back cameras should be placed along the midline of the treadmill, while the side camera should be placed at 90° to the location where the center of your hips will be while running. If you're using the camera on your phone, go to the settings and select 120 frames per second. Next, get on the treadmill and run at a self-selected pace for

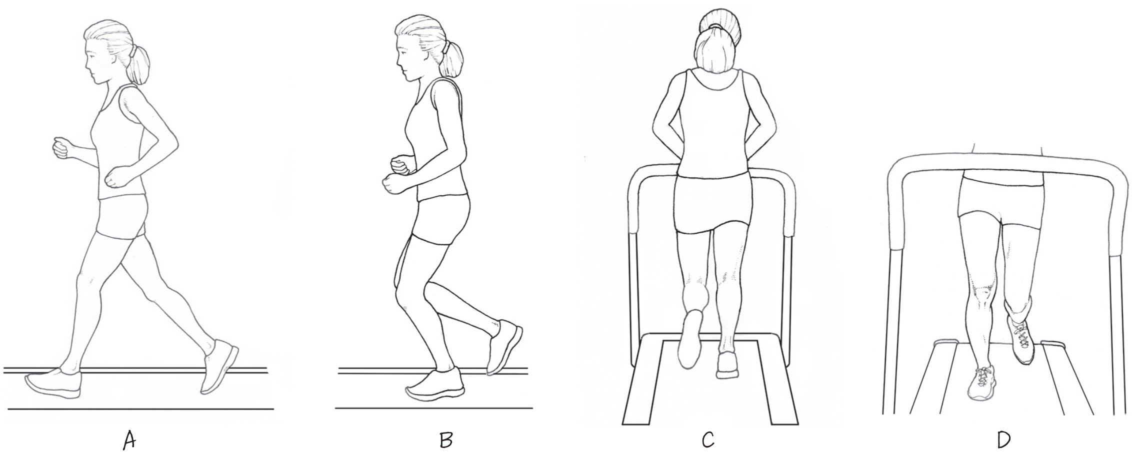


Fig. 4.8. ***Still frame images taken from each camera, corresponding to precise phases of the gait cycle.*** *Image* ***A*** *represents the position of your body at initial contact, while images* ***B***, ***C***, *and* ***D*** *are views from the side, back, and front during midstance.*

about five minutes. After you're warmed up, you'll only need a few minutes to perform the gait analysis.

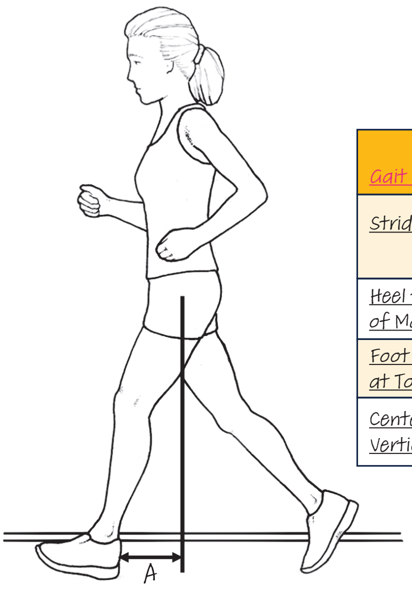
Once the cameras are recording, you'll need about two minutes of video from each of the three positions. Again, it's not necessary to have all three cameras going at once, but it does make things simpler. When finished, you'll need to extract specific still frame images from each camera that correspond to precise phases of the gait cycle (Fig. 4.8). You can import the videos into any of a variety of software programs that allow you to mark specific angles on the selected shots.

In the following sections, the clinical significance of each measurement is described, and recommendations are then made for improving your running form by means of specific exercises, stretches, and/or gait retraining. Even though every runner has his or her own unique running style, almost all running styles fall within the parameters of this gait assessment. Information gleaned from completing your gait analysis will hopefully help you run faster and more efficiently as well as greatly reduce your overall risk of injury.

Initial Ground Contact

On the side view of the initial contact image (Fig. 4.8, A), draw a vertical line from the center of your hip to the treadmill (Fig. 4.9). Now measure the distance between the back of your heel and the vertical line (Fig. 4.9, A).

While most running experts tell you to make initial contact with your foot directly beneath your center of mass, this is only possible at extremely slow running speeds. Researchers from the University of Wisconsin proved that the location where your foot makes initial ground contact is dependent upon not just your stride length but also your cadence (21). These researchers took 45 recreational runners and had them vary their cadence from 5–10% above and below their preferred running cadence. The table on the right of Fig. 4.9 summarizes their results. Notice how the heel to center of mass distance decreased from 4½ to 2¾ inches (11.5 to 7 cm) when runners transitioned from their lowest cadence and highest stride length to their highest cadence and lowest stride length. The vertical



Gait Parameters	−10%	−5%	Preferred Step Rate	+5%	+10%
Stride Length	7⅓ feet (2.23 m)	7 feet (2.13 m)	6½ feet (1.98 m)	6¼ feet (1.90 m)	6 feet (1.83 m)
Heel to Center of Mass	4½ inches (11.5 cm)	4 inches (10 cm)	3⅗ inches (9.15 cm)	3 1/10 inches (8 cm)	2¾ inches (7 cm)
Foot Angle at Touchdown	7.9°	6.6°	5.5°	3.3°	1.2°
Center of Mass Vertical Excursion	4⅘ inches (10.7 cm)	3⅘ inches (9.65 cm)	3⅖ inches (8.25 cm)	3⅙ inches (8 cm)	2 9/10 inches (7.4 cm)

Fig. 4.9. ***Initial ground contact.*** *Measure the distance* ***A*** *from the back of your heel to a vertical line drawn from the center of your hip to the treadmill.*

excursion of the center of mass also flattened out as the runners increased their cadence.

One of the most fascinating parts of the study was how drastically and consistently the foot angle at touchdown changed as stride length increased. When initial ground contact was made with the foot 2¾ inches (7 cm) in front of the center of mass, the foot was at a near midline position relative to the ankle. As stride length increased and cadence decreased, the foot angle at touchdown consistently increased until it hit almost 8° when running at 10% below the preferred cadence. I feel the increased touchdown angle represents an attempt by these runners to decrease the braking forces by using their ankles to absorb shock as their stride lengths increased. Remember, extremes of foot position correlate with reduced impact forces while running (22). The forward-most position of 4½ inches (11.5 cm) associated with the longest strides wasn't even that large of a number.

In a study of elite runners participating in a 5K road race (23), both men and women made initial ground contact with the foot 13 inches (33 cm) in front of their center of mass. This extreme forward foot position was necessary in order to achieve the 11- to 12-foot stride lengths present in these athletes.

Sagittal Plane Angle at Initial Contact

From the side view at initial contact image (Fig. 4.8, A), measure the important sagittal plane angles **A**–**D** indicated in Fig. 4.10.

Angle **A** represents the foot touchdown angle. As mentioned in the previous section on initial ground contact, higher angles are often associated with excessively long stride lengths. The fastest most efficient runners typically make ground contact with the ankle in a near midline position. Subtle changes from slightly

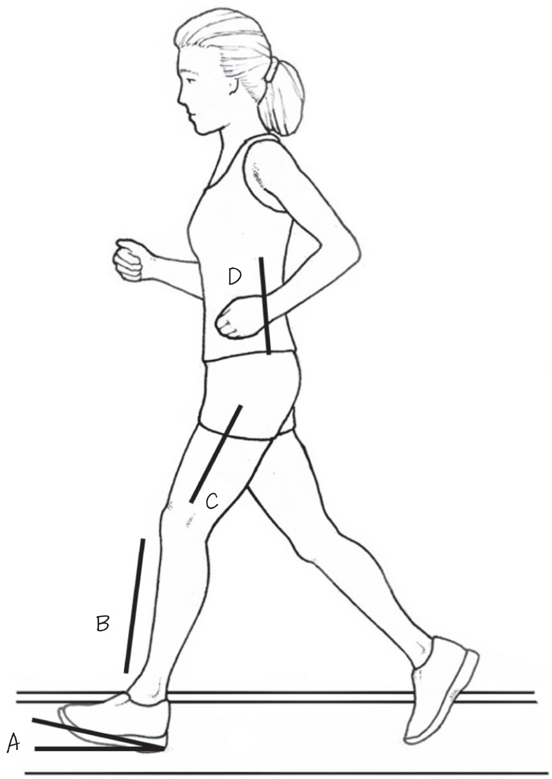


Fig. 4.10. ***Important sagittal plane angles taken from the side view at initial contact.*** *Measure the foot touchdown angle (**A**), the tibial inclination angle (**B**), the angle of the thigh relative to the vertical (**C**), and the forward lean of the trunk (**D**).*

plantar flexed to slightly dorsiflexed are a matter of individual preference, although most recreational runners are more efficient with a slight heel strike.

The most important angle in Fig. 4.10 is the tibial inclination angle **B**. This is the angle formed between the vertical and the longitudinal axis of the tibia and should be 7° or less. High angles correlate with inefficiency, decreased performance, and exaggerated braking forces (7). Runners with high tibial inclination angles often make a lot of noise when their lead foot hits the ground. An effective tool for gait retraining is to focus on hitting the ground softly and quietly.

Angle **C** is the angle of the thigh relative to the vertical at initial contact, and recreational runners tend to have between 20 and 25° of hip flexion at initial ground contact, while elite men and women have between 25 and 35°. The more forward position of the hip in elite athletes is related to their incredible stride lengths.

Angle **D** represents the forward lean of the trunk at initial ground contact. A slight forward lean offloads the knee, while a backward lean increases the risk of developing low back pain.

Peak Knee Flexion During Midstance

From the side view at midstance image (Fig. 4.8, B), measure the peak knee flexion angle (Fig. 4.11, A).

Most recreational runners tend to reach a peak knee flexion of around 40° by midstance. Slower hybrid runners tend to keep their knees a little stiffer, and it is not uncommon for a slow runner with a short stride to only flex the knee 25 to 30°. As long as you are keeping your stride length short, the smaller degree of knee flexion is not a problem and, in fact, can improve efficiency.

Because fast runners have such long stride lengths, greater degrees of knee flexion are necessary for adequate shock absorption. As mentioned, recreational runners typically bend their knees about 40° by midstance, but elite male and female distance runners average a little over 50° of knee flexion by midstance, with some runners bending their knees more than 65°. While excessive knee flexion can improve shock absorption, it is metabolically expensive and correlates with decreased efficiency.

Fig. 4.11. ***Peak knee flexion during midstance.*** *Measure the angle of peak knee flexion (**A**).*

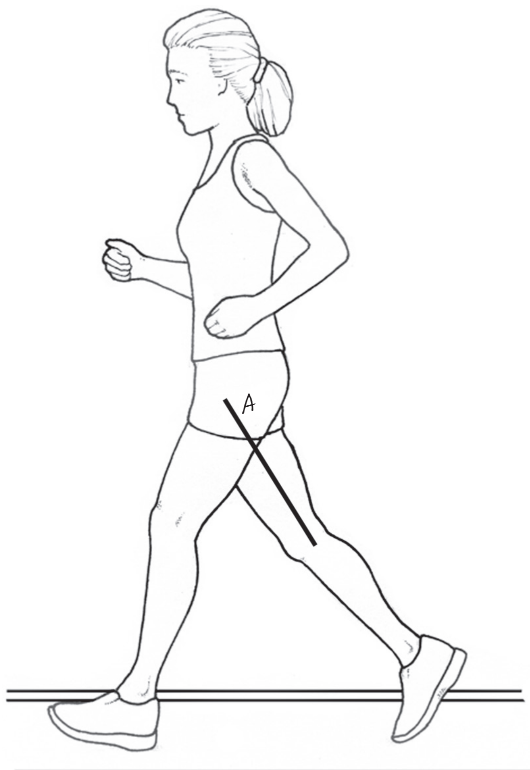


Fig. 4.12. ***Thigh extension during toe-off.*** *Measure the amount of thigh extension (**A**).*

Thigh Extension During Toe-Off

Measuring thigh extension during toe-off (Fig. 4.12, A). In my opinion, this is one of the most important measurements to take during the gait evaluation.

Slower recreational runners average 15 to 20° of hip extension by toe-off, while faster recreational runners extend their hips 20 to 30°. Because they have to generate so much force during midstance and propulsion, elite distance runners consistently average between 35 and 40° of hip extension by toe-off. This high number is necessary for the glutes and hamstrings to propel the center of mass forward as the hips extend through a larger range of motion.

Greater force generated through a larger range allows these athletes to accomplish the 10- to 12-foot stride lengths necessary to run sub-five-minute miles. While essential for elite marathon runners, almost all runners will benefit from strengthening their glutes and hamstrings and lengthening their hip flexors, which will allow them to generate more force as the leg extends farther behind them.

Knee Flexion of Swing Leg

Because 20% of all energy is spent to bring the swing leg forward while running, bending your knee (Fig. 4.13, A) improves efficiency by effectively shortening the length of the lever

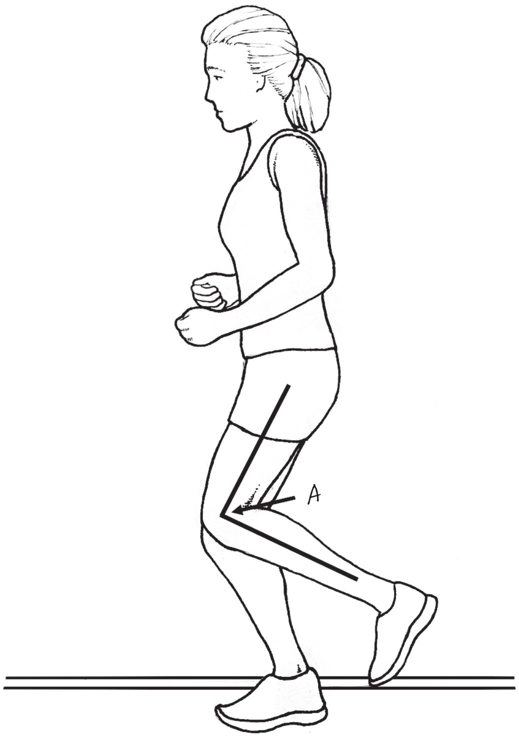


Fig. 4.13. ***Knee flexion of swing leg.*** *Measure the angle of knee flexion (**A**).*

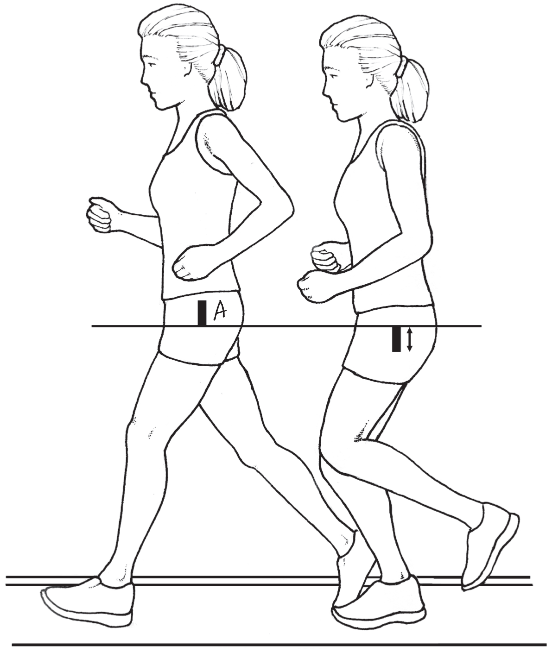


Fig. 4.14. ***Vertical excursion of center of mass during stance phase.*** *Stick a 2-inch (5 cm) strip of duct tape on the side of the hip (**A**). Mark a horizontal line along the top edge of the tape when at the lowest point and compare it to its position at the highest point (**arrow**).*

arm that your hip flexors have to work against (refer back to Fig. 4.3).

While recreational runners tend to flex their swing phase knee around 90°, elite male and female distance runners average 135° of knee flexion by midswing. Most recreational runners are fine with approximately 90° of flexion, but faster runners are encouraged to flex their knee a minimum of 130° during swing phase.

Vertical Excursion of Center of Mass During Stance Phase

The vertical excursion of the center of mass during stance phase is one of the most important predictors of speed and efficiency (7). To take this measurement, place a 2-inch (5 cm) piece of duct tape along the side of your hip, as shown in Fig. 4.14, A. Next, go through the side view video and freeze the frames where your center of mass is at its highest and lowest points. Place a horizontal line along the top edge of the tape when at the lowest point and compare it to its position at the highest point (Fig. 4.14, arrow).

In Fig. 4.14, the vertical excursion of the center of mass is 2 inches (5 cm) (1.0 times the length of the tape). If the upper distance was 1.5 times the length of the tape, the vertical excursion would be 3 inches (7.6 cm). This sounds complicated but it's really easy. Typical values for the vertical excursion of the center of mass vary between 1⁹⁄₁₀ and 4¹⁄₁₀ inches (5–10 cm), with the average vertical excursion being about 3 inches (7.5 cm) (7).

As mentioned, an excessive vertical excursion correlates with inefficiency and decreased performance. Like runners with an excessive tibial inclination at contact, those with too much vertical movement often make a lot of noise when striking the ground. This is especially apparent with treadmill running. The best way to reduce the vertical excursion of the center of mass is to stiffen your knees during contact, and focus on striking the ground softly. Learning how to run quietly is one of the most important things you can do to avoid injury and improve performance.

Side Bending of the Trunk

From the back view at midstance image (Fig. 4.8, C), measure the side bending of the trunk (Fig. 4.15, A). Ideally this angle will be less than 5°.

Runners with gluteus medius tendon problems and/or early hip arthritis will lean slightly toward the involved hip. Treatment in that situation is to strengthen the hip abductors, improve hip flexibility, and perform core exercises.

Lateral Pelvic Drop

The lateral pelvic drop is represented by the angle between a line drawn through the top of the pelvis and the horizontal (Fig. 4.16, A). Typical ranges of this angle for males are between 3 and 5° and for females, between 4 and 7°.

Excessive pelvic drop correlates with a wide range of injuries, including iliotibial band, anterior knee pain, and lateral hip pain (24). My favorite way to correct excessive pelvic drop is with the exercises illustrated in Fig. 3.36 (the isometric contractions in Fig. 3.36, B are particularly effective).

While excessive drop is almost always blamed on weakness of the hip abductors, new research suggests that some runners compensate for a weak gluteus maximus by firing the adductor magnus excessively during initial ground contact (25). The inappropriate co-contraction of the adductor magnus pulls the pelvis downward (Fig. 4.16, B), creating a pelvic drop that does not respond to conventional exercises. Because the adductor magnus functions as a hip extensor when the hip is flexed (Fig. 4.16, C), exercises to strengthen the glutes are ineffective because the adductor magnus takes over. That being the case,

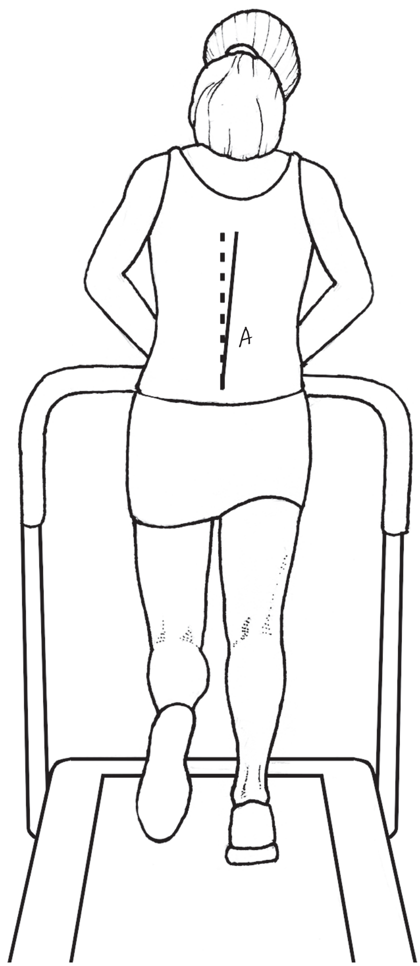


Fig. 4.15. ***Side bending of trunk.*** *Measure the amount of side bending of the trunk (**A**).*

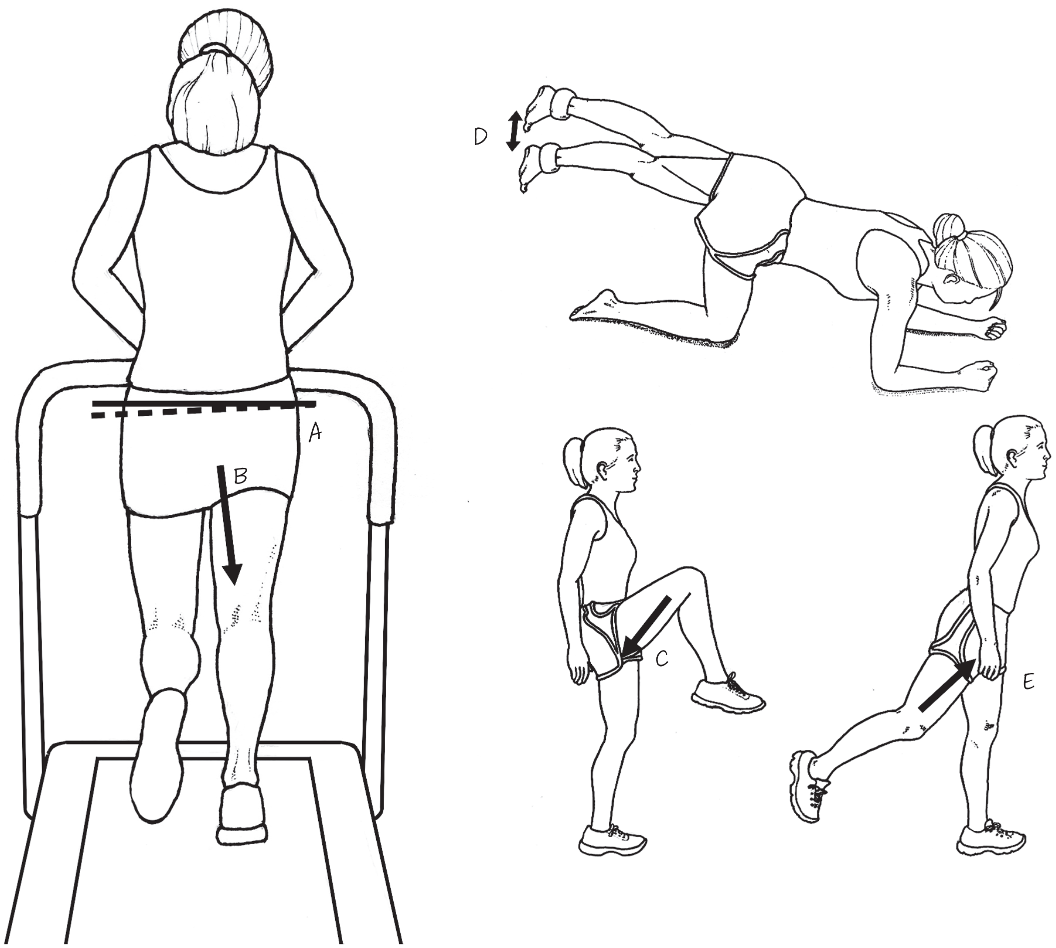


Fig. 4.16. ***Lateral pelvic drop.*** *Measure the angle between a line drawn through the top of the pelvis and the horizontal (**A**). Inappropriate co-contraction of the adductor magnus pulls the pelvis downward (**arrow B**), creating a pelvic drop. When the hip is flexed, the adductor magnus functions as a hip extensor (**C**), so it is recommended to perform glute exercises from neutral to extension only (**D**). When the hip is extended, the adductor is forced to behave as a hip flexor (**E**).*

I recommend runners perform glute exercises from neutral to extension only (Fig. 4.16, D), which forces you to fire just the gluteus maximus. The reason this exercise targets the gluteus maximus is that when the hip is extended, the insertion of the adductor magnus is displaced behind the axis of motion for the hip, forcing the adductor to behave as a hip flexor (Fig. 4.16, E). By exercising the gluteus maximus from neutral to extension, the adductor is unable to participate and the weak gluteus muscle eventually gets stronger. Performing 4 sets of 25 repetitions, four times a week for four weeks, is usually sufficient to strengthen the gluteus maximus so that the adductor magnus no longer takes over.

Arm Motions During Stance Phase

Typically, during stance phase the shoulder is extended 45° (Fig. 4.17, A), while the elbow is flexed about 70° (Fig. 4.17, B).

Fig. 4.17. ***Arm motions during stance phase.*** *Note the angles of shoulder extension (**A**) and elbow flexion (**B**). The hand should never cross the midline (**C**).*

There can be significant variation in the degree of elbow flexion, however, as typical ranges vary between 42 and 102° (23). While the degree of shoulder extension and elbow flexion don't correlate that strongly with efficiency, your hand should never cross the midline (Fig. 4.17, C), as excessive rotation of the torso does correlate with inefficiency (7).

Position of Center of Knee

A line drawn between the center of your hip and the center of your Achilles tendon should bisect the middle of the knee (Fig. 4.18, A).

In bowlegged runners, the line will bisect the inner side of the knee, while in knock kneed runners, the bisection line will traverse the outside of the knee. Bowlegged runners should do everything they can to strengthen the hip abductors, as strong hip abductors correlate with reduced progression of knee arthritis in these individuals (26). Knock kneed runners should strengthen their hip abductors and rotators. My favorite exercises are illustrated in Fig. 3.36. Lateral step-ups are important for both knock kneed and bowlegged runners because these exercises place less stress on the knee than squats and target the hip muscles more effectively.

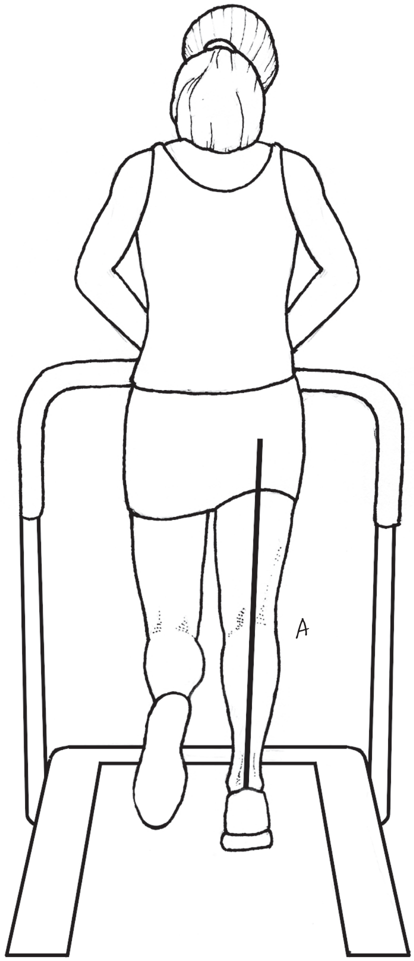


Fig. 4.18. ***Position of center of knee.*** *Observe where the center of the knee lies relative to a line drawn from the center of the hip to the Achilles tendon (**A**).*

Knee Separation During Midstance

When viewed from behind, there should be a slight separation of the knees during midstance (Fig. 4.19, A). Excessive narrowing correlates with valgus collapse of the knees, while an increased degree of knee separation is usually seen in bowlegged older males. When viewed from the front, the center of the patella should be in the middle of the knee during midstance (Fig. 4.19, B).

Excessive inward rotation of the knee (Fig. 4.19, C) decreases efficiency and greatly increases the risk of sustaining a running injury. The excessive rotation can be the result of anteverted hips, external tibial torsion, weak hip external rotators, and/or excessive pronation, and it is important to identify the exact cause of the issue and correct the faulty movement. This can be accomplished with hip strengthening exercises, accommodating external tibial torsion by landing with a slight toe-out running pattern while running, and/or using varus posts or orthotics to control excessive pronation.

Foot to Center of Mass Position

The inner aspect of the foot should always be lateral to a vertical line dropped from the center of mass to the treadmill (Fig. 4.20, A). An alternate way to take this measurement is to use a piece of chalk and place it down the center of the treadmill while it's running. This creates a temporary chalk line down the middle of the

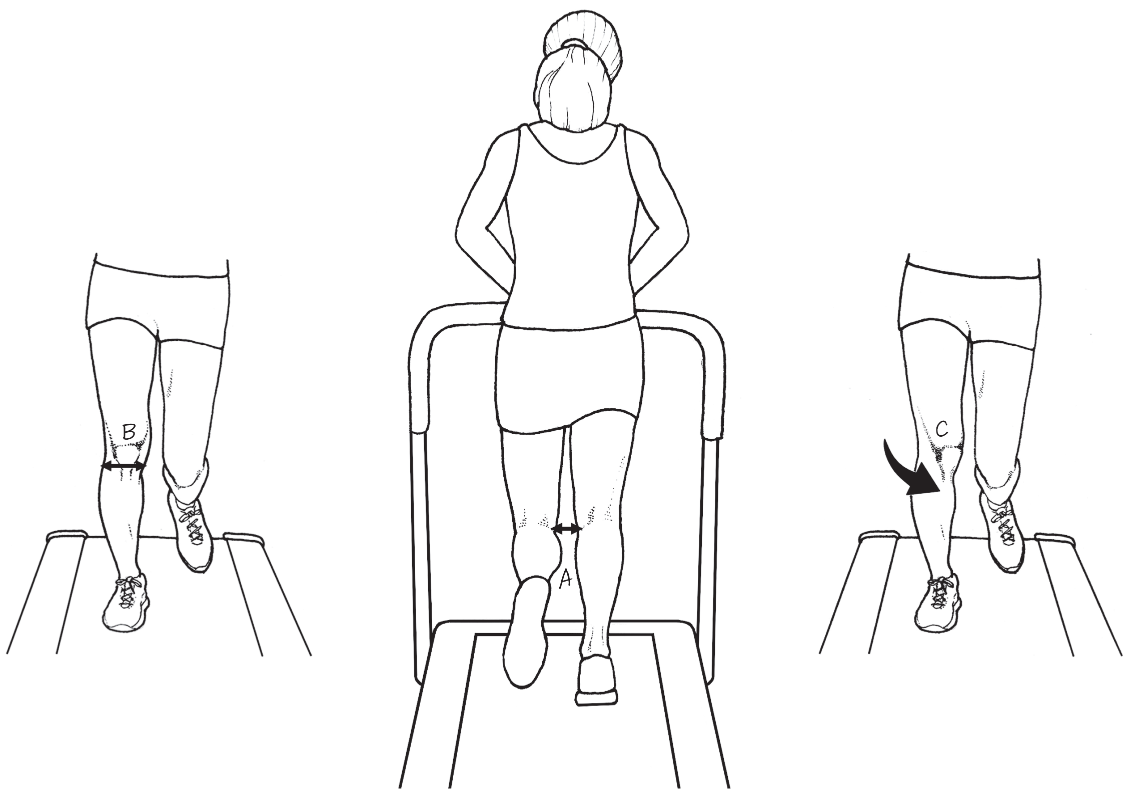


Fig. 4.19. ***Knee separation during midstance.*** *Determine the amount of knee separation (**A**). The center of the patella should be in the middle of the knee (**B**). Excessive inward rotation of the knee (**C**).*

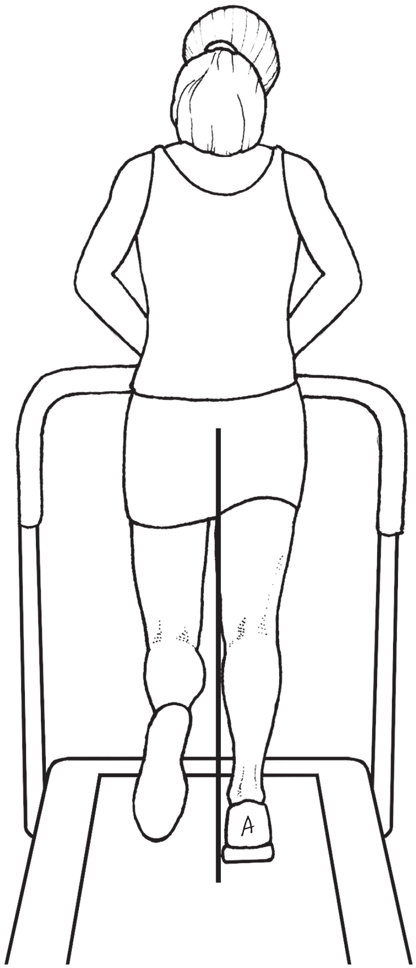


Fig. 4.20. ***Foot to center of mass position.*** *Check the position of the foot relative to a vertical line from the center of mass to the treadmill (**A**).*

treadmill, and the inner aspects of your running shoes should never cross this line.

In crossover gait patterns, the foot lands medially to the bisection line, which increases the risk of a wide range of injuries, including medial tibial stress syndrome, Achilles tendinitis, plantar fasciitis, and especially tibial stress fractures. Crossover gait patterns are problematic because the striking of the ground with the tibia at an angle increases the bending strains on the tibial cortex (27), which explains the connection between tibial stress fractures and crossover gait patterns (19). Common causes of crossover gait patterns include long stride lengths, low cadences, and/or weakness of the hip abductors.

In addition to reducing your stride length and strengthening your hip abductors, correcting a crossover gait pattern almost always includes gait retraining, which involves the runner focusing on not letting either foot cross the midline while running on a treadmill positioned in front of a mirror. Most gym owners don't mind you putting a chalk mark along the center the treadmill belt, as it gradually disappears over time. Start out by running slowly and make sure each foot consistently lands on the outer side of that centerline. In difficult cases, I have runners place a Triple Stick Strap just below their hips and have them run slowly on a treadmill. The strap forces them to fire their hip abductors constantly during the gait cycle, which allows for rapid resolution of a crossover running pattern. Of course, you have to run slowly as you're getting used to the strap.

Position of Foot During Midswing and Midstance

During midswing, the longitudinal bisection of the foot should be straight. When external tibial torsion is present, this bisection rotates out (Fig. 4.21, A). If you do not have external tibial torsion and the foot rotates out, this could be the result of excessive pronation, a weak tibialis posterior, and/or a tight gastrocnemius.

In addition to stretching your calves and strengthening your hips and feet, outward rotation of the foot almost always requires gait retraining, where you consciously modify the position of your foot during push-off. You should

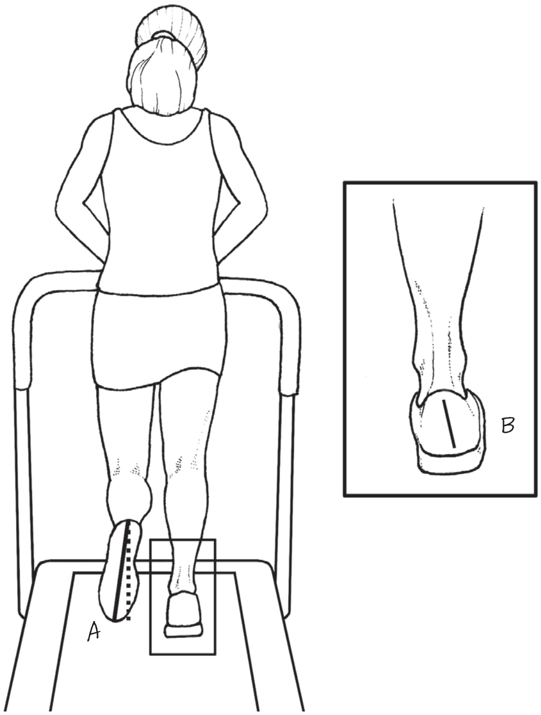


Fig. 4.21. ***Position of foot during midswing and midstance.*** *The longitudinal bisection of the foot should be straight, but rotates out if there is external tibial torsion (**A**). Identifying the rearfoot position during midstance (**B**).*

know your specific degree of tibial torsion on each side and try to match that degree while running. It's fine to land with your feet at angles less than your degree of torsion as long as your knees point straight forward.

Fig. 4.21, B illustrates how to identify the rearfoot position during midstance. Typically, the bisection of the heel should be vertical during midstance, but when excessive pronation is present, the vertical bisection of the heel rolls inward. Excessive pronation correlates with the development of Achilles injuries, medial tibial stress syndromes, and anterior knee pain. In contrast, runners with high arches present with their heels inverted and are more likely to develop stress fractures, lateral knee pain, and outer hip pain.

Overpronators should consider performing foot strengthening exercises and/or wearing minimalist shoes throughout the day, since overpronators who are strong are less likely to be injured (28). Runners who are overpronators almost always prefer stability running shoes, while high-arched runners prefer soft running shoes (see Chapter 5 for details regarding the selection of running shoes). High-arched runners should also consider doing gait retraining, where they try to reduce impact sounds during initial contact. As mentioned in Chapter 3, high-arched runners should work on maintaining adequate range of foot and ankle motion and learn to strike the ground with the tibia nearly vertical in order to reduce braking forces.

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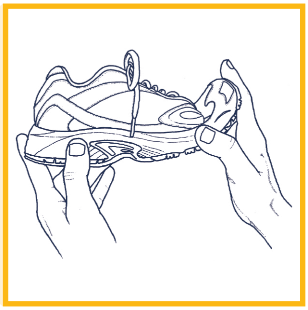
CHAPTER 5

SELECTING THE IDEAL RUNNING SHOE



Given the potential for lacerations, abrasions, and/or thermal injury, it seems odd that for almost all of our seven-million-year history as bipeds, we got around the planet barefoot. Although we perceive our feet as being delicate structures in need of protection, when barefoot from birth, the human foot is remarkably resilient. In a study comparing lifelong shod feet with the feet of people who have never worn shoes, researchers from Belgium confirmed that the unshod forefoot is 16% wider than the shod forefoot (1). The increased width allows for improved distribution of pressure while walking and running. In their analysis of pressure centered beneath the forefoot in lifelong shod versus unshod individuals, the authors confirmed that regular shoe use is associated with significantly more pressure being centered directly beneath the middle of the forefoot. When barefoot from birth, your toes become so strong that they push down with more force, distributing pressure away from the center of the forefoot toward the tips of the toes. This is consistent with an analysis of skeletal remains dating back 100,000 years, confirming that people who are barefoot from birth get less forefoot arthritis because their strong toes distribute pressure more effectively (2). To enhance protection against perforation, the skin of an unshod foot becomes extremely tough and is remarkably similar to leather. These features allowed the feet of our earliest ancestors to effectively manage the stresses associated with moving around sub-Saharan Africa.

Surprisingly, our unshod feet could even handle the extremely cold temperatures and jagged mountainous terrain associated with traversing Eurasia, as evidence suggests that we did not begin routinely using protective footwear until 30,000 years ago. This means that for 80,000 years following our exodus from Africa, we crossed the Swiss and Italian Alps and quickly spread through the cold climates of Europe and Asia without protective shoe wear. Remember, the fat pads beneath our feet contain 4.5 times the amount of polyunsaturated fat as conventional fat, and the reduced viscosity associated with greater amounts of polyunsaturated fats insulates our soft tissues from even subzero temperatures. The skin on the bottom of our feet also developed the peculiar ability to create a variable surface depending on whether we walk on slippery wet rocks or smooth dry terrain. Have you ever wondered why only the skin on the bottom of your hands and feet wrinkles when you get out of a bath or shower? Neurobiologists from a research lab in Idaho (3) claim that these wrinkles act like treads on a tire to improve our ability to grasp wet surfaces. In contrast, we have better traction on dry surfaces when our skin is smooth. Notice how the world's fastest race cars can take turns at 240 mph on dry surfaces by having perfectly smooth tires, while these same tires would be disastrous when driving in the rain, as they would hydroplane.

THE FIRST EVIDENCE OF SHOE USE

Determining the exact date we began routinely using shoes has been difficult, since the early shoes were made of leather, grass, and other biodegradable materials that left no fossil evidence. Although Neanderthals were suspected of occasionally using insulated foot coverings, the first direct evidence of shoe use dates back to only 3,500 years ago (Fig. 5.1). While primitive sandals and moccasins discovered in Oregon and Missouri have been carbon dated to 10,000 years ago, the actual time period that our ancestors first introduced protective shoe wear remains a mystery.

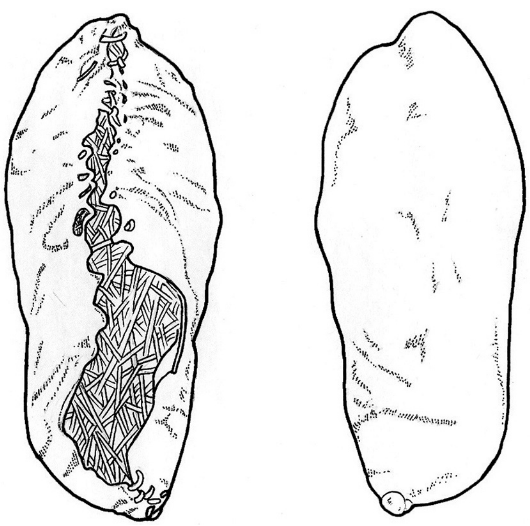


Fig. 5.1. ***The earliest shoes resembled stitched leather bags.***

To get around the fact that ancient shoes rapidly decayed, leaving no evidence of use, Trinkaus and Shang (4) decided to date the initiation of shoe wear by searching for changes in the shapes of the toes of our early ancestors. Because regular shoe use lessens strain on the toe muscles, the authors theorized that habitual shoe use would be associated with the sudden appearance of a thinning of the proximal phalanges (the bones at the base of our toes). By precisely measuring all aspects of toe shape and composition, the authors discovered a marked decrease in the robusticity of the toe bones during the late Pleistocene era, approximately 30,000 years ago (Fig. 5.2).

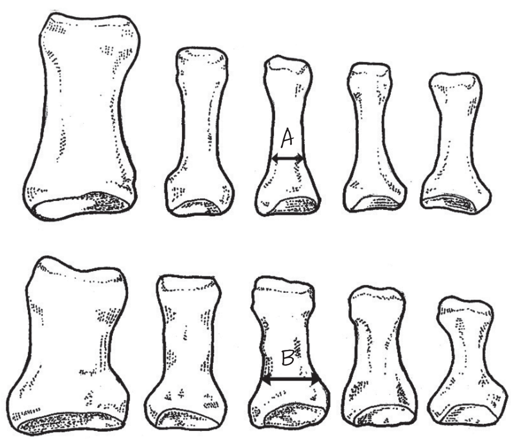


Fig. 5.2. ***Compare the width of the toe bones from the early (bottom row) and late (top row) Pleistocene era.*** *Trinkaus and Shang (4) claim that the decreased strain on the toes associated with regular shoe use produced bony remodeling with a gradual narrowing of the toe bones (compare* ***A*** *and* ***B****).*

Because there was no change in overall limb robusticity, the anatomical inference is that shoe gear eventually resulted in the development of narrower toes. The authors state that because there is no evidence of a meaningful reduction in biomechanical loads placed on human lower limbs during the late Pleistocene era (e.g., reduced foraging distances), the logical conclusion is that the thinner toes could only have only resulted from the use of shoes. The authors evaluated numerous skeletal remains from different periods and concluded that based on the sudden reduction in toe diameter, the use of footwear became habitual sometime between 28,000 and 32,000 years ago.

The first shoes were most likely similar to the shoes discovered in the Armenian cave; i.e., they were simple leather bags partially filled with grass to insulate the foot from cold surfaces. Because shoe gear varied depending on the region, the earliest shoes worn in tropical environments were most likely similar to the 3,000-year-old sandals recently found in Israel. Once discovered, the use of protective shoe wear quickly spread. The early Egyptians were believed to be the first civilization to create a rigid sandal, which was originally made from woven papyrus leaves molded in wet sand. Affluent citizens even decorated their sandals with expensive jewels.

While wealthy Greeks and Egyptians had separate shoes/sandals made for their right and left feet, the practice of wearing different shoes on each foot was short-lived, and throughout the Dark and Middle Ages, shoes were made to be worn on either foot. Improvements in manufacturing techniques before the American Civil War changed that. By modifying a duplicating lathe used to mass produce wooden gunstocks, a Philadelphia shoemaker was able to manufacture mirror-image lasts that allowed for the production of separate shoes for each foot. (Lasts are three-dimensional foot models used for the manufacturing of shoes.) Using this new technology, the Union Army supplied over 500,000 soldiers with matching pairs of right and left leather shoes.

ATHLETIC SHOES FROM THE EARLY 1900S

Leather continued to be the most popular material used for making shoe gear until the late 1800s, when Charles Goodyear accidentally dropped rubber into heated sulfur, creating vulcanized rubber. Prior to his serendipitous discovery, rubber was a fairly useless material because it melted at relatively low temperatures. The newfound resiliency of this material would have numerous applications, including the production of the first athletic shoe. Although alternative names for the new footwear include tennis shoes, trainers, and runners, the term "sneaker" became the most popular, and its origin can be traced back to an 1887 column in the *New York Times* (5), quoting an article from the Boston *Journal of Education*: "It is only the harassed schoolmaster who can fully appreciate the pertinency of the name boys give to tennis shoes—sneakers." Apparently, the soft rubber soles allowed schoolchildren to sneak up quietly on unsuspecting teachers.

Spalding manufactured one of the earliest athletic shoes: the Converse All-Star. Used by athletes at Springfield College to play the newly invented game of basketball, the All-Star was immediately popular. Since their introduction in 1908, more than 70 million pairs of Converse have been sold worldwide. In 1916, the US Rubber Company introduced Keds, an athletic shoe made with a flexible rubber bottom and canvas upper comparable to the Converse All-Star. The first orthopedic athletic shoe was developed by New Balance shortly before the Great Depression. New Balance continues to be the world's largest manufacturer of athletic shoes available in different widths. The German shoemaker Adi Dassler formed Adidas in the 1930s, while his brother Rudi formed Puma in the 1940s. Adidas was the more popular company and was the dominant manufacturer of sneakers until the 1960s, when Phil Knight and Bill Bowerman created Blue Ribbon Sports. Renamed Nike Inc. in 1978, after the Greek goddess of victory, this company has remained the world's largest producer of athletic shoes and sporting apparel for more than 50 years.

RUNNING SHOES FROM THE 1970S THROUGH 2010

The design of the first sneaker manufactured specifically for running was simple: A thin rubber sole was covered with a canvas upper, providing nominal cushioning and protection. The next generation of running shoes was built with thicker midsoles possessing large medial and lateral heel flares designed to improve stability. Unfortunately, the lateral heel flares were quickly proven to increase the potential for injury, as they provided the ground with a longer lever for pronating the rearfoot during heel strike (6) (Fig. 5.3). While this research was published in the late 1980s by one of the top biomechanists in the world, shoe manufactures were slow to respond and continued to include lateral flares for years to come.

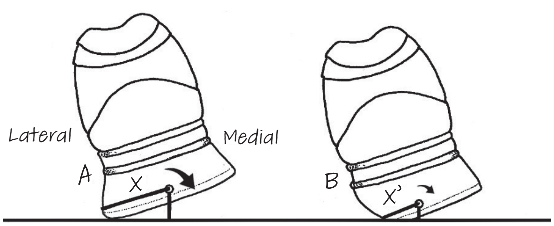


Fig. 5.3. ***The first running shoes were made with large lateral flares (A), which provided ground reaction forces with a longer lever arm (X) for pronating the rearfoot at heel strike.*** *This feature produces significant increases in the initial range and velocity of pronation. Note that a midsole with a negative flare (**B**) provides ground reaction forces with a shorter lever arm (**X'**) for pronating the rearfoot.*

The most significant design change from the flimsy running shoes of the 1960s was that manufacturers began to build sneakers to fit runners with one of three different arch heights: cushion sneakers for high-arched runners, stability sneakers for neutral-arched runners, and motion control sneakers for flat-footed overpronators (Fig. 5.4).

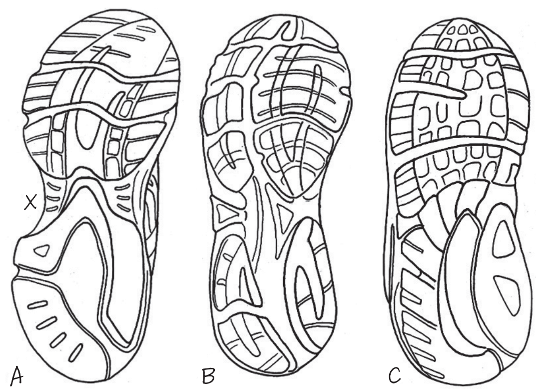


Fig. 5.4. ***Bottom view of the three types of running shoe.*** *Cushion sneakers (**A**) are made for individuals with high arches. They are slightly curved to match the shape of the typical high-arched foot and possess flexible midsoles with significantly less bulk in the midfoot region (**X**). The reduced midsole material in the midfoot gives the shoe an hourglass appearance when viewed from below. Stability sneakers (**B**) are suited to individuals with neutral foot types. They are straighter and have slightly more midsole material reinforced beneath the arch. In contrast, motion control sneakers (**C**) are very straight and are strongly reinforced throughout the midfoot with extra-thick midsole material. Because of the additional midsole material, motion control sneakers are extremely stiff.*

The vast majority of midsoles were made of polyurethane (PU) or ethylene vinyl acetate (EVA). Polyurethane is the most resilient of these materials because it provides maximum resistance against compression without breaking down. It can be identified by its weight (it is the heaviest midsole material), and by its tendency to turn yellow over time. In contrast, EVA is lighter but breaks down quicker, as it rapidly deforms with repeated impacts. As a result, EVA was often used in entry-level sneakers because it's inexpensive to produce.

Other hybrid midsole materials were later incorporated into midsoles, such as Phylon, which is made from EVA pellets heated and cooled in a mold, and Phylite, a combination of Phylon and rubber. Both of these materials could be injection-molded and easily shaped. Because Phylite is durable enough to be used without an outsole, it makes for an extremely light and flexible sneaker.

The density of the different midsole materials varies considerably and this is useful when designing sneakers for runners with high and low arches. High-arched runners need the least dense midsoles to improve shock absorption, while overpronators usually require a blend of midsole materials with soft material incorporated into the lateral midsole and firm material used along the medial midsole. Referred to as a "dual-density midsole," the softer material on the outer side softens the impact forces and decreases the initial velocity of pronation, while the firmer material on the inner side provides protection against excessive pronation (7). The dual-density midsole essentially creates a functional rearfoot varus post that lessens the amount of rearfoot pronation following heel strike.

Despite early thick midsoles providing cushioning and motion control, one main drawback of them was their weight. Because a running shoe is located so far from your hip, it has a very long lever arm to your hip muscles, forcing these muscles to work harder to accelerate and decelerate the added weight. It's comparable to sitting on a seesaw when the person on the other side suddenly moves farther back: Because the person's body weight suddenly has a longer lever arm to the pivot of the seesaw, you get stuck in the air. In regard to running, every 100 grams (3.5 oz.) of midsole material you add to a running shoe increases the metabolic cost of running by 1%. This is known as the "1% rule," and the increased exertion associated with accelerating and decelerating a heavy midsole can be extremely fatiguing over the course of a marathon.

Until recently, the heels of running shoes were almost universally elevated with an additional ⅜ to ½ inch (10 to 12 mm) of midsole material to support and protect the heel from impact forces. Unlike the flat Converse All-Star and Keds, the forward portions of the early midsoles were also modified by adding different degrees of toe spring (Fig. 5.5).

Fig. 5.5. ***The typical running shoe is manufactured with a toe spring (A), which allows the foot to move in a more natural manner and reduces strain on the Achilles tendon and plantar fascia.***

The toe spring modification, which represents a superior angulation of the far end of the midsole, effectively shortens the functional length of the shoe while also allowing the toes to move through reduced ranges of motion during propulsion. This midsole design is invaluable in the treatment of Achilles tendinitis, plantar fasciitis, metatarsal stress syndrome, and/or bunion pain, as it allows to the foot to go through push-off with a rolling action.

Running shoe manufacturers were positive that, compared to the flimsy sneakers of the 1960s, running shoes specifically designed to match the biomechanical needs of runners with different arch heights would not only reduce the risk of injury but also improve performance.

Some argue that the long-term use of excessive toe springs would result in weakness of the intrinsic muscles of the arch.

In 2010, several quality studies evaluated whether or not the prescription of running shoes based on arch height had merit. In one of the largest studies done to date, Knapik et al. (8) divided 1,400 male and female Marine Corps recruits into two groups: an experimental group in which running shoe recommendation was based on arch height, and a control group that wore neutral stability running shoes regardless of arch height. After completing an intensive 12-week training regimen, the authors concluded that prescribing running shoes according to arch height was not necessary, since there was no difference in injury rates between the two groups.

In another study evaluating the value of prescribing running shoes according to arch height, Ryan et al. (9) categorized 81 female runners as supinators, neutral, or pronators, and then randomly assigned them to wear neutral, stability, or motion control running shoes. Again, the authors concluded that there was no correlation between foot type, running shoe use, and the frequency of reported pain. One of the more interesting findings of this research was that the individuals classified as pronators reported greater levels of pain when wearing the motion control running shoes, which didn't surprise me, as these shoes are often as stiff as a board.

THE MIDSOLE

Problems Associated with Too Much Midsole Material

Throughout the 1980s and 1990s, researchers from Canada questioned the belief that cushioning the foot by adding more midsole material would protect against injury (10, 11). They claimed that highly cushioned running shoes might increase the potential for injury, as people are unable to feel the ground properly. To prove this, they poked small metal balls into different spots along the bottom of the foot and determined that the skin beneath the first metatarsal head is nearly 10 times more sensitive to pressure than the skin beneath the heel. The increased sensation beneath the first metatarsal allows the sensory receptors to produce a reflex contraction of the toe muscles when these receptors are stimulated while walking and running. As the toes push down to offload the sensitive first metatarsal head, they distribute pressure over a broader area, effectively negating the heavy loads centered beneath the metatarsal heads (Fig. 5.6). This research explains why over 100,000 years ago, our ancestors rarely developed arthritis in the joints of their forefeet, while we regularly get severe arthritis and bunions in those joints now.

In 1997, Robbins and Waked (10) did a simple test to evaluate the effect that soft materials have on our ability to respond to impact. They measured the impact forces as healthy subjects stepped off a perch onto a platform 1⅘ inches (4.5 cm) below. The platform was made from 0, 1, 2, or 3 inches (0, 2.5, 5, or 7.5 cm) of EVA foam. Paradoxically, the subjects landing on the thickest foams had the highest impact forces. The authors claim that because soft surfaces make it difficult to feel the ground properly, the subjects hit the softer surface harder by reducing their knee and hip flexion so they could compress the foam and thereby feel the surface better. They reference another interesting study showing that gymnasts landing on soft 4-inch (10 cm)-thick mats generate 20% more impact force than when they land on a hard floor (12). The only problem

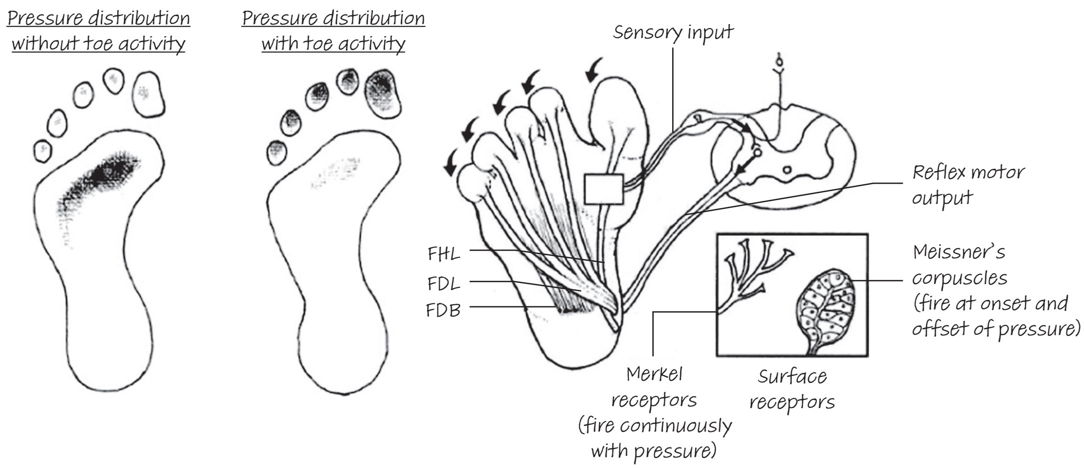


Fig. 5.6. ***When stimulated, the skin receptors located beneath the first metatarsal head produce a reflex contraction of the toe muscles, which transfers pressure away from the central forefoot to the tips of the toes.*** *This reflex contraction protects our forefeet from injury. (**FDB** = flexor digitorum brevis; **FDL** = flexor digitorum longus; **FHL** = flexor hallucis longus.)*

with Robbins and Waked's research is that the subjects were landing on 1–3 inches (2.5–7.5 cm) of EVA foam, which at the time was way more foam than you could fit into a running shoe.

Problems Associated with Too Little Midsole Material

Given the fact that excessive midsole cushioning can increase impact force and reduce efficiency (remember the 1% rule), it might seem that the best midsole would be no midsole at all. While this is often suggested by advocates of barefoot running, the complete removal of a midsole may result in chronic injury because some degree of midsole cushioning is necessary to protect the heel and forefoot fat pads from trauma. Researchers from the Netherlands have proven that barefoot running results in a 60% deformation of the protective fat pad beneath the heel, while running with running shoes with conventional midsoles results in only a 35% deformation of the fat pad (13). When repeated tens of thousands of times over your running career, the 60% deformation may permanently damage the walls of your protective fat pads, resulting in chronic heel and/or forefoot pain.

In addition to extending the lifespan of your heel pads, research proves that the softer running shoe midsoles are capable of storing and returning energy, offsetting the reduced efficiency associated with its added weight. By studying oxygen consumption while runners ran either barefoot or with running shoes having 10-mm-thick midsoles, researchers from the University of Colorado proved that despite the added midsole weight associated with wearing running shoes, there is no difference in efficiency when running barefoot and running with cushioned midsoles (14). The authors state: "The positive effects of shoe cushioning counteract the negative effects of added mass, resulting in the metabolic cost for shod running approximately equal to that of barefoot running."

One of the more intriguing results of this study was that the researchers also evaluated efficiency as the runners ran on specially designed treadmills fitted with ⅖ and ⅘ inch (10 and 20 mm) of midsole material attached directly to the treadmill belt. Interestingly, the treadmill fitted with 10-mm-thick midsole material produced the same improvement in efficiency as the treadmill fitted with 20-mm-thick midsole material. Apparently, just as flexible running tracks providing ¼ inch (7 mm) of deflection allow for the fastest running times (refer back to page 55), ⅘ inch (10 mm) of midsole cushioning provides the ideal amount of energy return with less weight and only a minimal reduction in sensory perception. Remember, the EVA used in the research by Robbins and Waked (10) that resulted in increased impact forces was 1–3 inches (2.5–7.5 cm) thick, which was more likely to dampen sensory input and produce a paradoxical response to cushioning.

Changing the Midsole's Heel-to-Toe Drop

As mentioned, throughout the 1980s, 1990s, and early 2000s all running shoes were made with an additional ⅖ and ⅘ inch (10 and 20 mm) of midsole material, creating what is referred to as the "heel-to-toe drop" (or "heel-to-toe differential") (Fig. 5.7). This degree of heel elevation was considered essential for offloading

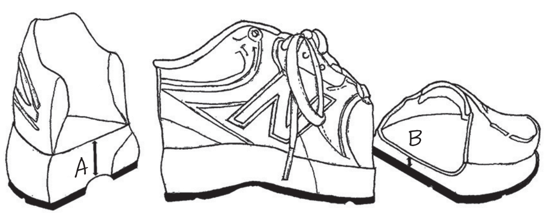


Fig. 5.7. ***The heel-to-toe drop is the difference in midsole thickness beneath the heel (A) and the forefoot (B).*** *This particular sneaker has ⅘ inch (22 mm) of midsole material beneath the heel, and ½ inch (12 mm) of midsole material beneath the forefoot, creating a ⅖ inch (10 mm) heel-to-toe drop.*

the Achilles tendon and absorbing impact force when the heel hit the ground. In an attempt to reduce weight and more closely duplicate the way the foot moves when barefoot, different manufacturers began to gradually reduce the amount of midsole material beneath the heel.

Zero-drop running shoes were eventually introduced with the same amount of cushioning in the forefoot and rearfoot and are often considered "more natural" because they allow your foot to function as if you were barefoot. Proponents of zero-drop shoes claim the excessive cushioning associated with the high heel-to-toe drop running sneakers cause you to strike the ground with a more pronounced heel strike, which also results in smaller knee flexion angles at touchdown, as well as less ankle dorsiflexion during midstance (15). Advocates of running shoes with a ½ inch (12 mm) heel-to-toe drop claim that the added cushioning in the heel provides comfort and protects the wearer from injuries.

To resolve the controversy regarding heel-to-toe drop, researchers from France had 553 runners wear running shoes manufactured with 0, ¼, ⅖ inch (0, 6, 10 mm) of heel-to-toe drop (16). The sneakers, which were identical except for the degree of heel elevation, were randomly prescribed and the runners were followed for six months. The fact that the shoes were identical except for heel elevation is what makes this paper significant: Because there are so many differences between different models of running shoe, it's impossible to evaluate the effect of one factor without controlling all other factors. Prior studies evaluating the effect of heel height can't guarantee that their outcomes were actually the result of the heel-to-toe drop or some other attribute of the shoe.

At the end of the six-month French study, while there was no overall difference in injury rates, a lower risk of injury in occasional runners was linked to the 0 and ¼ inch (6 mm) heel-to-toe drop running shoes, while experienced runners wearing the 10 mm heel-to-toe drop shoes were less likely to be injured. Although this was just one study, it tallies with what I've observed in practice in that faster high-mileage runners prefer sneakers with $\frac{2}{5}$–$\frac{4}{5}$ inch (10–12 mm) of heel-to-toe drop, while slower recreational runners do well with 0 and ¼ inch (6 mm) heel-to-toe drop models. As with midsole stiffness and weight, the heel-to-toe drop is an important factor associated with improved comfort, and you should experiment with different models until you find the midsole height that feels best for you.

RUNNING SHOES FROM 2010 TO CURRENT
MINIMALIST RUNNING SHOES

Inspired in part by the popular book *Born to Run* by Christopher McDougall, minimalist running shoes were initially designed to mimic barefoot running (Fig. 5.8). According to the paleoanthropologist Daniel Lieberman,

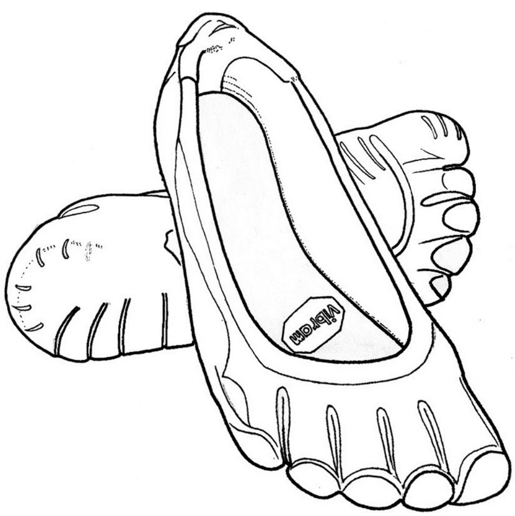


Fig. 5.8. ***The Vibram FiveFingers running shoe is designed to mimic barefoot activity.***

to protect their heels from injury, barefoot runners naturally switch to a more forward contact point, which theoretically improves the storage and return of energy and more effectively dampens impact forces (17).

While the possibility of improved energy return and dampened impact forces sounds appealing, it is necessary that runners wearing minimalist shoes actually switch to the more forward contact point in order to obtain these benefits. Unfortunately, this is not always the case. In a study of runners transitioning to minimalist shoe wear, 35% of the runners continued to make ground contact with their heels in spite of wearing the minimalist shoes for more than two years (18). Although runners with midfoot strike patterns may benefit from minimalist shoes, slow runners who continue to strike the ground with their heels are more likely to be injured, since vertical loading rates beneath the heel are nearly 40% higher with a minimalist shoe when rearfoot striking (19). Furthermore, research showing that a 10-mm-thick midsole does not reduce efficiency, since it improves the storage and return of energy, suggests that even fast runners can afford the protection provided by conventional midsoles (14).

Another problem with minimalist shoe wear is that you are more likely to be injured while breaking them in. In a frequently cited study published in *Medicine and Science in Sports and Exercise*, researchers from Brigham Young University noted that 10 out of 19 runners transitioning into minimalist shoes became injured, compared to only one out of 17 runners in the control group wearing conventional running shoes (20). I feel that the high injury rate linked to minimalist shoes has everything to do with the fact that modern foot architecture is significantly different than that of our barefoot ancestors. Remember, the early hominids had robust toes and forefeet that were 16% wider than ours, so they could easily manage the forces associated with the push-off phase of running. In addition to having stronger, wider forefeet, our ancestors were also tiny. *Homo erectus*, the first hominid to routinely run, was only 5 feet 2 inches (1.57 m) tall and weighed about 110 pounds. Given the tiny stature and wide forefeet of these hominids, it's not surprising that heavier male runners are much more likely to be injured while wearing minimalist shoes (21).

In the most detailed studies of minimalist shoes to date, researchers from Australia (22) evaluated the short- and long-term effects of wearing minimalist shoes as runners gradually transitioned from 0–100% minimalist shoe use for their daily runs. For the first six weeks of the study, the authors had 50 recreationally competitive male runners gradually transition into wearing minimalist shoes for 35% of their total weekly running mileages. All runners were habitual rearfoot strikers and had been accustomed to conventional running shoes. After the 6-week break-in, runners were instructed to continue transitioning into the minimalist shoes by increasing their allocated use by 5% each week for an additional 20 weeks. At the 6- and 20-week marks, researchers measured running performance, running economy, calf strength, lower limb bone mineral density, stride length, and cadence.

By week six of the study, runners transitioning into minimalist shoes showed slight improvements in running economy and performance, which the authors attributed to the reduced weight of the minimalist shoes. Two of the 50 runners switched from a heel to a forefoot contact point during the first six weeks. When the study finally concluded after 20 weeks, regular use of minimalist running shoes was shown to have absolutely no effect on performance, running economy, stride length, cadence, bone mineral density, or even point of initial contact (the two runners who transitioned to a forefoot contact reverted to their typical rearfoot strike by week 20). Significantly, the minimalist shoes did slightly increase ankle plantar flexor strength, which was consistent with prior research demonstrating that eight weeks of running in minimalist shoes increased intrinsic foot muscle cross-sectional area (23). The authors state that because of the limited benefits linked to using minimalist shoes for 100% of their training, runners "may need to consider limiting minimalist shoe use to lower percentages of total training volume because greater minimalist shoe volume has been previously associated with increased injury risk."

My takeaway from this study is that when worn throughout the day while walking and/or for brief periods of slow running, minimalist shoes favorably stimulate the muscles of the arches and calves without overloading them, often resulting in significant increases in strength and volume of the muscles of the arches and legs (23). Over time, this may result in not just strength gains, but also an improved ability to store energy in the muscles and tendons of the arches and legs, and return energy to them. This statement is supported by the fact that compared to runners wearing conventional running shoes, experienced minimalist runners have larger and more resilient Achilles tendons (24). Increases in muscle strength and tendon resiliency can have long-term benefits, especially in master's runners, who slow down as they age, not because of decreased force output in their hips or knees but because their calves weaken as they get older (25).

MAXIMALIST RUNNING SHOES

At about the time the popularity of minimalist shoes began to fade (in part due to the high injury rates), an obscure French company named Hoka One One came out with the first maximalist running shoe: the Mafate (Fig. 5.9).

Fig. 5.9. ***The Hoka One One Mafate can have as much as 1½ inches (37 mm) of midsole cushioning (A).***

The company name originates from the Maori language, meaning "to fly over earth," and the One One portion of the name is pronounced Oh-nay On-nay. The earliest Hoka models were specifically designed to help runners manage the extreme impact forces associated with fast downhill running, by stacking huge amounts of midsole material into the shoe. Because these shoes are so thick, the term "stack height" was developed to refer to the total amount of shoe material between the foot and the ground. It's usually expressed by two numbers: The first stack height number is the thickness beneath the heel, and the second is the thickness beneath the forefoot. Compared to zero-drop minimalist shoes with a stack height of ½/½ inch (12/12 mm), it is not uncommon for maximalist shoes to have stack heights of well over 1⅕ inches (30 mm). The Hoka One One Bondi, for example, has a stack height of 1½/1¼ inches (37/33 mm).

Immediately popular with the ultra-running community, maximalist shoes have been catching on with recreational runners. Other running shoe manufacturers have noticed the success of the maximalist shoes, and companies such as Altra, Vasque, New Balance, Brooks, and Adidas have developed their own models, each with its own unique shape, stack height, and heel-to-toe drop.

Because of the excessive midsole material, you would think that maximalist shoes would increase impact forces, according to the original research published by Robbins and Waked as previously discussed. In fact, initial research suggested that wearing maximalist shoes did indeed increase impact force. In 2018, researchers from Oregon State University compared vertical ground reaction forces between the Hoka One One and a traditional New Balance running shoe (26). Consistent with prior research on the relationship paradox between midsole thickness and impact force, the subjects wearing Hoka One Ones had significantly higher impact forces and loading rates than those wearing conventional running shoes. The results of this study were in agreement with one study (27) but in conflict with another (28). The problem with all of these studies is that the researchers compared completely different running shoes, which have too many different features to make a judgment possible about stack height alone.

In 2020, to determine the effect of stack height in isolation, researchers from San Jose State University performed a detailed study comparing ground reaction forces and three-dimensional motion as 20 recreational runners ran in three different types of running shoe: maximalist, traditional, and minimalist (29). Unlike prior studies, these researchers used the same running shoe in each category (New Balance Boracay) and they just varied the stack height for each shoe: The maximalist shoe had $1\frac{1}{4}$ inches (33 mm) rearfoot and $1\frac{1}{5}$ inches (29 mm) forefoot cushioning, the traditional had $\frac{4}{5}$ inch (22 mm) rearfoot and $\frac{7}{10}$ inch (18 mm) forefoot cushioning, and the minimalist had $\frac{2}{5}$ inch (10 mm) rearfoot and $\frac{1}{4}$ inch (6 mm) forefoot cushioning. Other than the thickness of the midsoles, the shoes were all identical.

After analyzing the three-dimensional motion and impact forces associated with the different shoes, the authors determined that runners wearing the maximalist shoes pronated much farther than runners wearing the traditional and minimalist shoes. The excessive rolling-in was especially apparent as the runners were pushing off. The authors state that "the eversion mechanics in the maximal shoe may place runners at a greater risk of injury." Previous research has linked a wide range of lower limb and leg injuries to excessive pronation (30, 31). Despite the potential for increasing pronation, many of the maximalist models are gaining popularity, not just in the running community but also in professions such as nursing, where foot pain is the number one cause of occupational injury. After a brief break-in period, the altered movement patterns identified with wearing maximalist shoes would more than likely self-correct.

NEW CATEGORIES: FAST, SOFT, OR STABLE

Given the new changes in structure and function of the latest running shoes, the old categories of cushioning, stability, and motion control are no longer adequate for classifying all the new models. To that end, many experts now categorize running shoes as fast, soft, or stable. In keeping with the 1% rule, the fast models are lighter and typically possess slightly lower heel drops than the other models. The stable shoes tend to weigh just slightly more than soft models, but often possess reinforcement struts and/or plates embedded in their midsoles to provide support.

What makes all of these models different from their clunky predecessors is that almost every manufacturer now uses its own high-tech midsole foams, which provide stability and cushioning at a fraction of the weight of the early PU/EVA midsoles used in the 1980s and 1990s. Most of the new midsoles incorporate proprietary mixes of TPU (thermoplastic polyurethane) beads, lightweight EVA, various bags containing gel or air, and/or Pebax, the amazingly lightweight thermoplastic polymer made from polyamide blocks for strength and polyether for flexibility.

In the soft models, Salomon worked with Dow Chemicals to create the Sonic 3 Balance, which contains one layer of a memory-like foam to absorb shock, and another layer that is light and responsive. Another popular soft model is the Asics Nimbus. In addition to its special gel lining that wraps its heel, the Gel-Nimbus 22 has a layer of lightweight FlyteFoam Lyte placed on top of a full layer of FlyteFoam Propel, a high-rebound elastomer to provide extra spring during push-off. The New Balance Fresh Foam X 1080 was voted Editors' Choice among soft running shoes by Runner's World in 2020. What I like about this model is that the Fresh Foam midsole has a molded heel made with a deep pocket that wraps around the back of the foot to eliminate unwanted movement. In my opinion, a well-fitting heel counter is one of the most important things to look for when choosing a running shoe. Another popular soft running shoe is the Adidas Adizero Boost range. The midsole of this shoe is made with Adiprene, a proprietary blend of urethane polymers cured with special chemicals to enhance strength and resilience. This unique foam retains the ability to absorb shock even at subfreezing temperatures. Adiprene is highly effective at storing and returning energy, which is why these shoes are so frequently worn by the world's fastest runners.

Unlike the heavy motion control shoes of the past, several of the new stability models come in weighing less than 10 ounces (284 g). The Nike React Infinity Run Flyknit weighs only 9.6 ounces and is designed with a wide forefoot, a flared midsole, and a slight ramp beneath the midfoot, which is designed to "give your foot proprioceptive cues." Whether this is true or not is open for debate, but I've been working with different people in the running shoe industry for decades and most of them didn't know what proprioception was 30 years ago so I look at this statement as a sign they're moving in the right direction. Another stability shoe, the Mizuno Wave Inspire Waveknit, has special reinforcement plates embedded in the midsole near the inside of the medial arch. These plates provide additional support should your foot roll in too much. The New Balance 860 stability shoe has kept its varus posts to control motion, but the ramp angle has been reduced to make it feel smoother. In contrast, in the Brooks Adrenaline the rearfoot post has been scrapped all together in favor of more subtle changes to the shape of the midsole.

When it comes to fast running shoes, the hands-down winner is the Nike Air Zoom Alphafly NEXT% (who names these things?). Eliud Kipchoge made history wearing these shoes by being the first person to run 26.2 miles in under two hours. Nike boasts that regardless of skill level, the Alphaflys and their predecessor, the Vaporflys, can improve economy by as much as 4%, which translates into a 3.4% increase in speed for the world's fastest marathon runners, and a 4% improvement in speed for three-hour marathon runners (32). While shoe companies can be like politicians in that they have a tendency to tell you what you want to hear, the claims of 4% improvements in performance and economy may actually be true. In addition to weighing less than 7 ounces (200 g), the Alphaflys have special air chambers located beneath the forefoot (called "air pods"), and a graphite plate has been embedded in the midsole that can store and return energy during propulsion (Fig. 5.10). (Think of the graphite poles used in pole vaulting: They bend as the athlete is starting to ascend and then snap back again to propel them over the high bar.)

What really makes the Alphafly and Vaporfly shoes so fast is the new Pebax midsole, which is uncommonly compliant and resilient. In a 2017 study published in *Sports Medicine*, Wouter Hoogkamer and his colleagues (32) had 18 high-caliber runners complete a series of five-minute running trials wearing one of three shoes: the Nike Zoom Streak 6 (midsole lightweight EVA with a rearfoot airbag and a 23/15 stack height), the Adidas Adizero Adios Boost 2 (TPU midsole with a 23/13 stack), and the Nike Vaporfly ZoomX (Pebax midsole with an embedded carbon plate and a 31/21 stack height). After equalizing the weights by adding lead pellets to the lighter shoes, the examiners measured oxygen consumption and CO_2 production as the elite runners ran at different speeds on different days. At the end of the study, the subjects wearing the Vaporflys lowered their metabolic cost of running by a shocking 4%. Even more impressive, this 4% improvement occurred at every running speed on every day of the study. The only drawback was that athletes wearing the Nike Vaporflys had slight increases in their stride

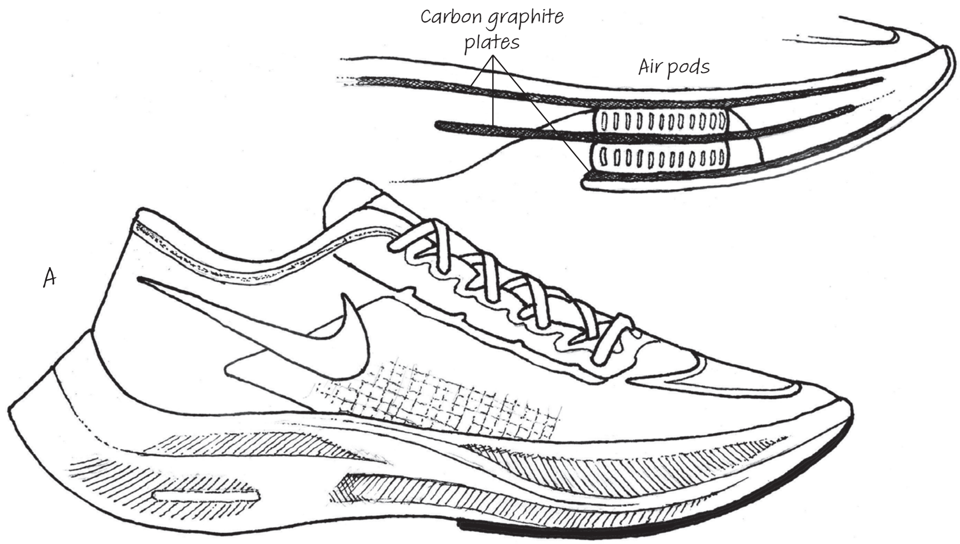


Fig. 5.10. ***The Nike Vaporfly (A) has a graphite plate embedded in the forefoot between two layers of Pebax foam.*** *The Nike Air Zoom Alphafly NEXT% (top) has three carbon graphite plates (arrows) with four separate air pods located beneath the forefoot (two on each side).*

lengths and impact forces, which could translate into a greater prevalence of hamstring and/or knee injuries.

While the carbon plate may have played a slight role in the improved economy, it more than likely was the Pebax midsole, which has just the right blend of stiffness and energy return. The authors claim that to improve performance, a midsole must have high compliance (the ability to deform) and high resilience (the ability to return energy). They use the example of running on a sandy beach: The sand is compliant, so you sink into it, but it's not resilient, so you have to work hard to push forward. Like a springy indoor track, Pebax midsoles come close to that perfect blend of compliance and resilience. The high compliance makes it so you don't have to flex your knees and hips to absorb shock, while the resilience offloads your arch muscles by returning free energy.

Dr. Hoogkamer and his colleagues didn't measure joint motion so it's not possible to determine exactly why the runners became so efficient. Whatever the mechanism, these shoes represent the most innovative changes in shoe production since Goodyear discovered rubber. Critics of the new technologies claim that the shoes provide an unfair advantage, and as of February 2020, World Athletics decided to ban shoes containing more than one rigid embedded plate or blade and/or any shoe that had a sole height greater than 1⅗ inches (40 mm). The actions of World Athletics reminded me of the 2008 Olympics in Beijing, where Speedo introduced a full-body swimsuit that reduced the drag from water resistance. After athletes wearing the suits shattered dozens of world records, the International Swimming Federation took only a few months to ban all full-body swimsuits from competition.

An important point about these running shoes that no one has discussed is that all of the tests to date have been done on elite athletes. The ability of a midsole to store and return energy is dependent upon the ability of the midsole material (or air pods) to compress just the right amount so that the stored energy can be returned.

The midsole compliance and resilience that works for a 130-pound (60 kg) elite male running at a 4:30 minute/mile pace would probably not work that well for a heavier and slower recreational runner. Think of the springs on a pogo stick. If a 200-pound (90 kg) male got on a pogo stick designed for a 70-pound (30 kg) child, he would quickly stretch the spring to its maximum length, have a lag period, and then have to use his own legs to jump up. Conversely, if a 70-pound child got on a pogo stick designed for a 200-pound male, he or she wouldn't be able to stretch the springs enough for the pogo stick to work. Midsole materials are comparable to pogo stick springs in that they have to be adjusted to match the weight of the person using them.

In regard to running, the midsole/air pods would also have to be adjusted depending upon running speed, which affects the forces beneath the foot. Nike claims that the pressure and size of the air pods will someday be adjustable in order to maximize individual performance, although the cost of customization may be prohibitive. In my opinion, rather than looking to footwear to improve your ability to store and return energy, you'd be better off doing specific exercises and drills to enhance your tendon resiliency. In the 2017 paper evaluating the Vaporflys, Dr. Hoogkamer and his colleagues state that "regardless of the shoes worn, in human running, the vast majority of the mechanical energy storage and return occurs within our natural biological structures." To me, that sentence speaks volumes.

SELECTING THE RUNNING SHOE THAT'S RIGHT FOR YOU

Assuming you don't have a company like Nike bending over backward to design the perfect running shoe for your particular mechanics, given all the different companies and models out there, it can be a bit overwhelming trying to find the running shoe that's right for you. Some experts continue to claim that you should pick a shoe on the basis of your arch height, while others recommend that you should pick a shoe on the basis of how much pronation you may or may not have. To resolve the controversy, Dr. Nigg looked at the relationship between running shoe prescription and running injuries and determined that when runners self-select running shoes on the basis of comfort alone, they are much less likely to be injured (33). Dr. Nigg also proved that self-selected comfortable running shoes improve efficiency by reducing oxygen consumption. Apparently, you may not have to spend $250 on a pair of Vaporflys to get slight improvements in efficiency.

The only problem with Dr. Nigg's research is that it only included studies up to 2014. According to the latest research, high-mileage recreational runners should avoid zero-drop shoes and stick to running shoes with a minimum of ⅓ inch (8 mm) heel elevation, while low-mileage runners would probably do better with a 0 to ¼ inch (6 mm) heel drop sneaker (16). Because they increase rearfoot pronation during contact (29), maximalist shoes should be avoided by beginner runners unless the fit is perfect and they feel really comfortable. That being the case, then by all means buy them but take your time breaking them in. You could also consider doing some preemptive tibialis posterior exercises to reduce the rate of rearfoot pronation associated with using maximalist shoes. I've also noticed that unlike the motion control models from the 1980s and 1990s, runners who pronated excessively prefer stability shoes, while high-arched runners prefer soft shoes. Early motion control models, such as the Brooks Beast, have been replaced with more comfortable, flexible models that can decelerate the velocity of pronation and provide support without bulk. Softer models have been proven to decrease impact forces, which is why high-arched runners find them so comfortable.

If you're a serious runner and looking to get that extra 4% associated with the Nike Vaporflys, consider reducing your stride length for the first few weeks of breaking them in. Remember, Hoogkamer and his colleagues (32) showed that Vaporflys produced slight increases in impact forces and stride lengths, which could increase the risk of a hamstring injury. Because hamstring strains have over a 70% annual reinjury rate, the slight improvement in performance would be meaningless if you're unable to run. As when wearing rearfoot eversion and maximalist shoes, your hamstrings should quickly adapt to the slight increase in stride length that can occur with wearing the Vaporflys. You could also do preemptive eccentric hamstring exercises to prevent injury.

Because the most important predictor of comfort is that the shoe fits your foot perfectly, you should know how to check length, width, and fit of the heel counter. To check length, make sure you're fitting the running shoe to your larger foot (everyone has slight differences between right and left shoe size) and when standing, the tip of your longest toe should be about the width of your thumbnail from the end of the shoe. Selecting the proper shoe width, in both the forefoot and the rearfoot, is essential. The widest part of the forefoot of the shoe should match the location of your metatarsal head. As mentioned previously, you should always look for a running shoe that cradles your heel firmly (Fig. 5.11).

In a paper published more than 30 years ago, Jorgenson (34) proved that a snug heel counter

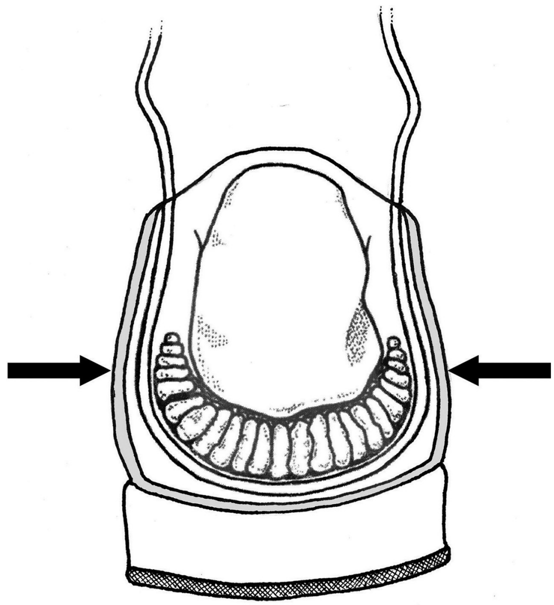


Fig. 5.11. ***A firm heel counter (arrows) compresses the sides of the rearfoot, preventing the calcaneal fat pad from displacing from beneath the bottom of the foot.*** *No synthetic material comes close to matching the shock-absorbing capabilities of the human fat pad.*

has the ability to reduce impact forces at foot strike, decrease activity in the quadriceps and calf musculature during stance, and improve overall efficiency (33). The impressive outcomes in this study can be traced directly to the fact that a snug heel counter prevents displacement of the calcaneal fat pad, which has been proven to absorb shock better than any synthetic material. Although Pebax didn't exist at the time, I'm sure that if a head-to-head comparison between the calcaneal fat pad and Pebax were performed today, your fat pad would win hands down.

The bottom line when it comes to purchasing a running shoe—rather than listening to an expert on running shoes tell you what shoe is right for you, trust your own judgment. For just as runners intuitively know how to self-select their ideal stride length while running, so too they apparently know how to self-select the ideal running shoe.