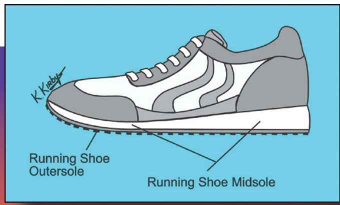

The Biomechanics of Running Shoes

Research has led to better shoe design and improvements in comfort, cushioning, and performance.

BY KEVIN A. KIRBY, DPM

Goals and Objectives

1) To learn how running shoe design modifications may affect rearfoot pronation during running

2) To understand the concept of midsole durometer

3) To understand how a dual-durometer rearfoot midsole alters rearfoot pronation during running

4) To understand how running shoe midsole construction may affect the impact forces of running

5) To comprehend the difference between material tests and human tests when evaluating running shoe midsoles

6) To learn how the central nervous system may alter the stiffness of the lower extremity during running on different surfaces

7) To better comprehend how running shoe midsoles may reduce the metabolic cost of running

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*An answer sheet and full set of instructions are provided on pages 152-154.—**Editor***

In the late summer of 1972, few Americans ran for recreation and pleasure. However, this relative lack of interest in distance running in America all seemed to change when, during the Munich Summer Olympics, two athletes from the USA, Dave Wottle and Frank Shorter, won gold medals in the 800 meters and marathon, respectively. After these gold medal performances, Americans became much more interested in distance running, and thus was one of the important contributing factors to what is now called the "running boom" in America.[1]

Cavanagh and LaFortune, in 1980, discovered that most of their experimental subjects had rearfoot foot strike during running.

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The increase in popularity in distance running over the past 45 years has resulted in an estimated 15 million Americans who run on a regular basis for pleasure, recreation, and competition.[2]

In the early days of running shoes, before 1972, their soles were very thin and had only a single layer of rubbery material to grip the ground, providing very little cushioning. The running shoes of today, however, are highly complex biomechanical garments, with synthetic uppers and multi-component midsoles and outersoles that are designed to be lightweight, cushioned, and responsive to the foot of the runner.[3] The vast number of running shoe models available today, with their bright multi-colored upper materials and their varied midsole and outersole designs can be, at times, overwhelming for runners and medical professionals alike.

The running public expects that their podiatrist will be the medical professional with the best knowledge of running shoe biomechanics. As a result, podiatrists need to be aware of the most important research on

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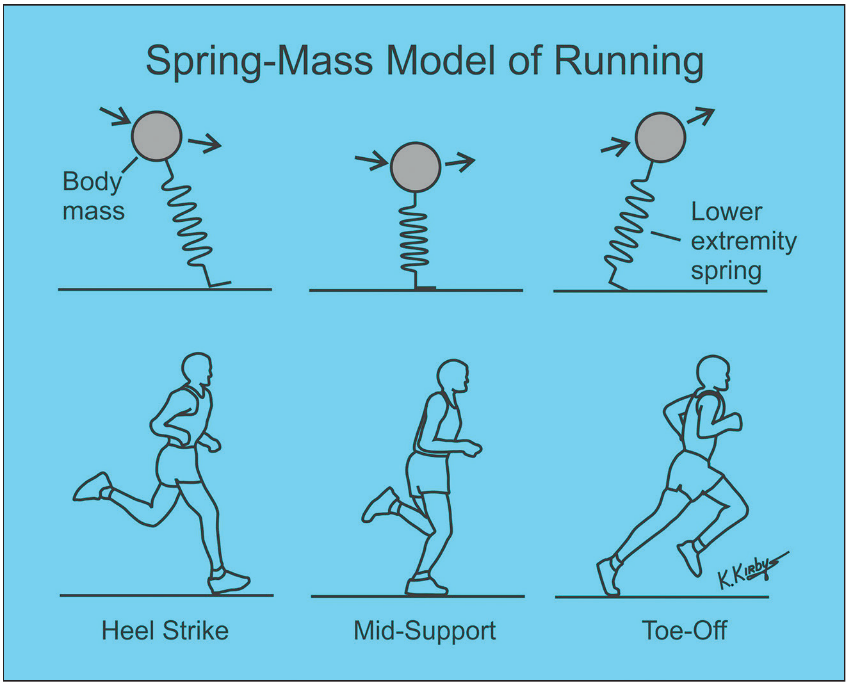

Figure 1: According to classic running biomechanics research by Cavanagh and LaFortune in 1980, runners landing on the proximal third of the running shoe sole are rearfoot strikers, runners landing on the middle third of the sole are midfoot strikers, and those runners landing on the distal third of the sole are forefoot strikers.

The midsole located in a running shoe is located between the insole and outer-sole of the shoe.

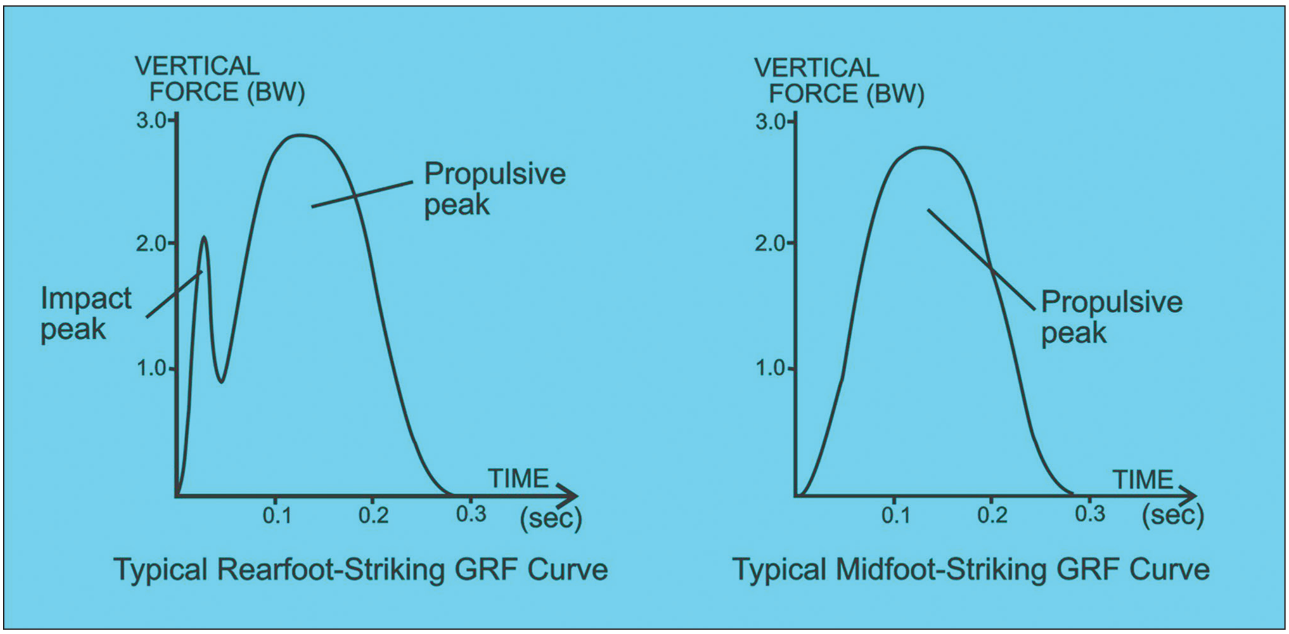

Figure 2: Rearfoot strikers demonstrate a different shape in their ground reaction force versus time curves during running compared to midfoot strikers. Rearfoot strikers have a high frequency impact peak that is caused by initial contact of the heel of the running shoe with the ground that is followed by a lower frequency propulsive peak caused by the center of mass of the runners passing over the planted foot. Midfoot strikers only demonstrate the propulsive peak during running due to a lack of heel strike.

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the biomechanical effects of running shoes that has occurred over the years. Unfortunately, prior to 1972, biomechanics laboratories were either non-existent or were very primitive, with little running shoe research being performed. Fortunately, over the past four decades, biomechanics laboratories have grown both in number and complexity.

Modern biomechanics laboratories are now equipped with sophisticated technologies such as force plates, in-shoe pressure sensors, pressure mats, three-dimensional motion analysis systems, and lightweight accelerometers that are linked to computers with specialized software to allow rapid and precise measurement of the kinematics and kinetics of running, both with and without running shoes. These advancements in technology have allowed the biomechanical researchers of today to understand the complexities of the mechanical effects of running shoes on the human body like no other time before. In the discussion that follows, the key scientific research that has been published by these biomechanics laboratories is reviewed in order to provide podiatrists an excellent knowledge of running shoe biomechanics for their runner-patients.

Impact forces during running are increased while running at lower velocities with very low durometer midsoles.

Effects of Running Shoes on Impact Forces During Running

Much of the early research on running shoes focused on the ability of the running shoe to absorb shock for the runner during the support phase of running. In 1980, Cavanagh and LaFortune, from the Penn State Biomechanics Lab, studied 17 trained runners who ran at 4.5 m/sec (5:58 mile pace) over a force plate. These researchers were the first to categorize runners as being either rearfoot strikers (12/17 subjects), midfoot strikers (5/17 subjects), or forefoot strikers (0/17 subjects). Not only was the vertical ground reaction force (GRF) found to be approximately 2.8 times body weight, rearfoot striking runners and midfoot striking runners had very different shapes to their GRF versus time curves (Figure 1). In the rearfoot striking runners, there was an initial high-frequency impact peak that corresponded to when the heel struck the ground, followed by a lower frequency propulsive peak that corresponded to when the body's center of mass (CoM) moved over the planted foot (Figure 2). The midfoot striking runners did not have the high-frequency impact peak but only had the lower-frequency propulsive peak in their GRF versus time curves.[4]

In order to reduce the impact forces inherent in running, shoe manufacturers began to design their running shoes, in the early 1970s, with a shock-absorbing layer of material within the shoe sole known as the midsole. The midsole is sandwiched between the insole board/fabric and the outersole of the running shoe (Figure 3). The hardness of the various midsole materials is measured in durometer, with lower durometer midsoles being more compressible and soft, and higher durometer midsoles being less compressible and hard.[5,6]

In 1985, Benno Nigg, while director of the University of Calgary Biomechanics Laboratory, reported on 13 subjects running at 3.5 m/sec (7:40 mile pace) in seven running shoes, which were identical in construction except for the rearfoot portion of their midsoles, which had durometer values of 20, 30, 35, 40, 45, 50 and 55. Drop impact tests were also performed where a 5 kg mass was dropped onto the rearfoot midsole of the running shoes to measure the impact forces registered with each shoe midsole. Even though, as expected, the drop impact tests measured less impact force in the midsoles with lower durometers, the softest running shoes midsoles (i.e. 20 and 30 durometer) caused the runners to experience more impact force than did the hardest midsoles. Also, the vertical impact forces measured by the subject running over the force plate did not significantly increase from the 35 to the 55 durometer midsole, even though the midsole was getting progressively harder.[7]

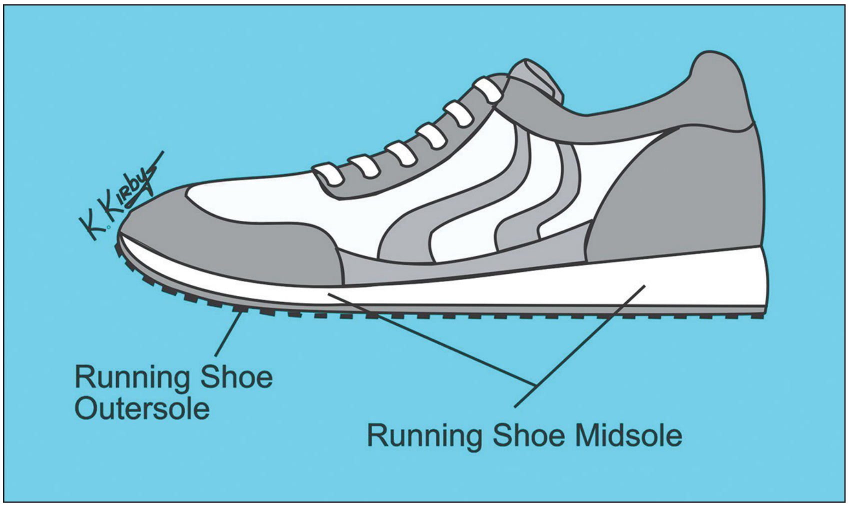

Figure 3: The sole of the running shoe is divided into two basic components, the outer-sole and midsole. The outer-sole is a relatively thin material which provides traction and is relatively resistant to abrasion when contacting the ground during running. The midsole is a relatively thick and cushioned material sandwiched between the outer-sole and the insole board/fabric of the running shoe.

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Nigg explained the paradoxical results as being partly due to a bottoming out effect that occurred when the runners wore the softest midsoles (i.e., 20 and 30 durometer). Bottoming out was thought to occur when the midsole material was so soft that the midsole compressed relatively fast and then suddenly stopped compressing, which resulted in higher impact forces. The authors also thought that having a shoe with a very soft midsole may do more harm than a harder midsole running shoe. Another important point from this research was that even though the GRF impact peak may be a good approximation of the internal impact forces experienced by the runner's body, the drop impact test, using a machine to measure midsole cushioning, was considered to be "not relevant with respect to impact force reduction in running".[12]

Nigg and co-workers also published important running shoe research in 1987 on how running velocity and midsole hardness affected the impact forces of rearfoot-striking runners. In their experiments on seven male recreational and seven male competitive runners, three pairs of identical shoes that had three different midsole durometers (25, 35, and 45 durometer) were worn by the subjects as they ran over a force plate at four different running velocities, 3 m/sec (8:56 mile pace), 4 m/sec (6:42 mile pace), 5 m/sec (5:22 mile pace) and 6 m/sec (4:28 mile pace).

Even though the impact force decreased slightly as the runner ran in harder midsole running shoes, the change was not significant. However, the vertical impact force did significantly increase with faster running velocities, demonstrating that running velocity increased the impact peak of running more than did altering running shoe midsole hardness.[8] Frederick and colleagues had also noted, six years earlier, an increase in vertical impact force peaks with increased running velocities.[9]

In a review of their research findings that vertical impact force peaks do not change appreciably with variations in running shoe midsole hardness (unless the midsole is so soft that it bottoms out), Nigg and co-workers noted that "common sense" would predict that smaller impact force peaks would occur while running on softer midsoles. However, the reality was that the subjects reacted differently than expected to variations in midsole hardness. Each runner, by using central nervous system (CNS) control, modified their landing strategy during running, depending on the midsole hardness "to keep the external impact force peaks constant". Therefore, the common assumption made then, and still even today, that midsole hardness can always be used to reduce impact forces during running is erroneous.[13]

Figure 4: In the spring-mass model of running, the runner's body is modelled as a mass supported by a lower extremity spring. The elastic muscle-tendon elements in the lower extremity of the runner are first compressed, like a spring, from initial contact with the ground to the middle of mid-support storing potential energy. This potential energy is then released as kinetic energy from the middle of mid-support to toe-off of running. The running shoe midsole, due to its elasticity, may also act as a spring in synergy with the spring of the lower extremity to decrease the metabolic cost of running.

Nigg and Bahlsen discovered Increased lateral rearfoot sole flare angle increased initial rearfoot pronation, but total pronation was not affected by increased lateral rearfoot sole flare angle.

Effects of Running Shoes on Rearfoot Pronation During Running

The question of whether running shoes could modify the amount, velocity, and accelerations of rearfoot pronation that occurred in running was studied in 1983 by Clarke and colleagues at the Nike Sport Research Lab. These researchers measured the frontal plane pronation and supination of 10 subjects running at a speed of 3.8 m/sec (7:03 mile pace) on a treadmill. Each subject wore 36 different shoes with different constructions, including shoes with three midsole durometers, three types of rearfoot sole flares, and four different heel-height differentials. The heel-height differential is the difference in thickness between the rearfoot sole and the forefoot sole (i.e., heel drop). The study showed that running shoes with softer midsoles (25 durometer) allowed the foot to reach a greater pronated position and have more total frontal plane rearfoot movement than did the shoes with either the medium midsole (35 durometer)

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or the harder midsole (45 durometer). In addition, running shoes with 00 heel flare allowed more rearfoot pronation than did running shoes with either 150 or 300 rearfoot sole flares. Heel-height differential was found to have no effect on rearfoot pronation.[10]

Dual-density midsoles in running shoes have a higher durometer midsole in medial rearfoot, and a lower durometer midsole in lateral rearfoot.

In 1988, Nigg and Bahlsen investigated the influence of running shoe rearfoot sole flare and rearfoot midsole hardness on rearfoot pronation and external impact forces. Fourteen male rearfoot-striking subjects ran at 4 m/sec (6:42 mile/pace) over a force plate with two-dimensional (2D) motion analysis in running shoes with a 160, 00, and a rounded lateral rearfoot sole, with midsoles of different hardness. They found that increases in the lateral rearfoot sole flare angle did increase initial rearfoot pronation, but did not have an influence on total pronation of the foot. Harder midsoles in shoes with a lateral heel flare did alter vertical impact force peaks but didn't alter impact peaks if the shoe midsole was soft.

The researchers suggested that the best running shoe construction to produce low initial pronation and low vertical impact force peaks would be a relatively hard midsole material with no lateral rearfoot sole flare.[11] Research from a year earlier also demonstrated that initial rearfoot pronation steadily decreased when the rearfoot portion of the shoe sole was changed from a pronounced flare to no flare and then to a rounded lateral rearfoot sole shape.[12]

From the results of available research of the time, Nigg and colleagues suggested that to reduce rearfoot pronation of the runner, the midsole material on the lateral portion of the rearfoot sole, where the force of impact first occurs, should be softer than the rest of the midsole. They suggested a dual-density midsole arrangement in the rearfoot midsole, with the softer midsole component being located laterally in the rearfoot and the harder midsole component being located medially in the rearfoot, in order to reduce rearfoot pronation during running. These researchers also found a drastic reduction in rearfoot pronation when they experimented with this dual-density rearfoot midsole construction in two runners who were "heavy pronators".[13]

Then, in 1980, from these research findings, Barry Bates, director of the biomechanics lab at the University of Oregon, was granted US patent #4363189 in 1982 for a "Running Shoe with Differential Cushioning" that incorporated the idea of a higher durometer medial midsole and lower durometer lateral midsole in the rearfoot of the running shoe in order to limit initial rearfoot pronation and also help reduce the vertical impact force peak during running.[14] The resultant dual-density rearfoot midsole idea was first introduced into the running shoe marketplace in the mid-1980s and is now an integral part of nearly all "stability" and "motion-control" running shoes of today.

Effects of Running Shoes on the Metabolic Cost of Running

Important in understanding the influence that running shoe midsole hardness and midsole thickness may have on the metabolic cost of running (i.e., the metabolic energy required to run at a given pace) is the concept that running is commonly modelled as being equivalent to a mass (representing the CoM of the body) being bounced along the ground by a lower extremity spring (Figure 4). This "spring-mass model" of running allows the effective transfer of potential and kinetic energy during running to increase the metabolic efficiency of running locomotion.[15,16]

Another critical factor that affects the metabolic cost of running is the concept that this lower extremity "spring" has a variable stiffness that is controlled by the CNS. Thomas McMahon and Peter Greene, of Harvard University, were the first to propose that the lower extremity may be modelled as a variable stiffness spring-like structure during running that adapts its stiffness depending on the stiffness characteristics of the running surface.[17]

McMahon and Green, in 1979, first proposed that the lower extremities of runners are like springs that have variable stiffness depending on the stiffness of the running surface.

McMahon and Greene's ground-breaking experiments involved constructing a single-lane running surface made of plywood boards supported by wooden rails that could be moved to alter the track stiffness. The goal of the researchers was to "tune" the stiffness of the running surface to best improve performance and reduce injury rates in runners. In their experiment, they used eight male subjects that ran at five to eight different running speeds on four track surfaces: concrete, a "pillow-track" made up of foam-rubber pillows, and two board tracks of intermediate compliance.

Their research found that having a running surface with very low

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stiffness (i.e., pillow track) resulted in a marked reduction in the runner's performance. However, on tracks of intermediate compliance (i.e., the two board tracks), their model predicted a slight speed enhancement with a decrease in foot contact time and an increase in step length, which was confirmed by their experimental findings.[19] McMahon and Greene's research on running surface stiffness tuning led to the construction of the first-ever indoor "tuned track" at Harvard University in 1977. The Harvard indoor "tuned track" ultimately allowed collegiate running athletes to shave five seconds from their mile times and reduce their rate of injuries.[18]

In 1980, research from Frederick and colleagues demonstrated that running shoes with air midsoles decreased the metabolic cost of running.

Soon after McMahon and Greene's landmark research on using springy surfaces to improve the metabolic efficiency of running, running shoe companies started to attempt to incorporate these "energy return" features into their running shoes. In 1980, E.C. Frederick and colleagues, from the Nike Sports Research Laboratory, performed research to discover whether shoes could be designed to reduce the metabolic cost of running. The researchers had 11 subjects run in both non-air-soled and air-soled type running shoes. The air-soled shoes, with midsoles containing an inflated air bladder under pressure, required 2.8% less metabolic energy than conventional EVA midsole running shoes.[19] Subsequent studies by Frederick, et al. showed significant improvements in metabolic efficiency when running in air-soled-style shoes.[20]

More recently, in 2012, Jason Franz and colleagues, from the University of Colorado Boulder Locomotion Lab, researched the metabolic cost of running in lightweight cushioned shoes versus running barefoot. They studied 12 male experienced barefoot runners at 3.35 m/sec (8:00 mile pace) running both barefoot and in lightweight cushioned running shoes (150 g per shoe). Small lead strips were attached to the shoes to determine the oxygen cost of mass being added to the feet of the runners. They found that the oxygen cost of running increased by approximately 1% for each 100 grams of mass added to the foot, whether barefoot or shod.

Barefoot and shod running did not differ in oxygen cost. However, the researchers did find that for experimental conditions with equal mass added to the foot, shod running required 3-4% less metabolic energy than running barefoot.[21]

Additionally, in 2014, Tung and co-workers used a unique experimental design to explore whether running shoe cushioning could, by itself, have an effect on the metabolic cost of running. They studied 12 midfoot-striking runners under four conditions: running barefoot on a normal treadmill, running in lightweight, cushioned running shoes on a normal treadmill, and also running on a treadmill with two "cushioned-belt" treadmill conditions, one with a 10 mm thick layer of ethylene vinyl acetate (EVA) foam attached and another with a 20 mm EVA foam layer attached to the treadmill belt.

In 2012, Franz and colleagues demonstrated that for equal mass added to the foot, shod running required 3-4% less metabolic energy than barefoot running.

Interestingly, running barefoot on the 10-mm-thick foam treadmill belt required 1.63% less metabolic energy than barefoot running without the foam cushion on the treadmill. The researchers also found that running with shoes and running barefoot on the treadmill with a normal belt required equal metabolic demands and hypothesized that the beneficial energetic effects of shoe cushioning was counterbalanced by the added mass of the shoe on the runners' feet.[22]

It is now commonly believed that the CNS of the runner will adjust the stiffness of their lower extremities to optimize it for the stiffness of the surface that they are currently running on. As noted above, McMahon and Greene first demonstrated this concept in 1979 in their experiments with running tracks with different surface stiffnesses.[19]

In addition, Daniel Ferris and colleagues from the University of California Berkeley Locomotion Lab showed that runners were able to adjust their lower extremity stiffness on their first running step onto a surface with a different surface stiffness. The runners in their experiment were also found to smoothly transition between different surfaces so that the path of their CoM during running was unaffected by the change in the stiffness of the surface they ran upon.[23]

Other researchers have also confirmed that runners will optimize lower extremity stiffness in response to running on surfaces of varied stiffness, whether the surface is part of the running shoe (e.g., running shoe midsole) or the surface is outside the running shoe (e.g. concrete, grass, track, or treadmill). This CNS-controlled mechanism of lower extremity stiffness optimization is most likely responsible for the changes in the metabolic cost when running on surfaces and/or shoes of varied stiffness.[24,25]

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Conclusion

The modern running shoe is very different from the shoes available to runners in 1972. Over the past four decades, scientists at modern biomechanics labs have provided excellent research evidence on how running shoes may affect the impact forces and rearfoot pronation inherent in running and may improve the metabolic efficiency of running.

Sophisticated research has led to better shoe design and improvements in comfort, cushioning, and performance of the modern running shoe. The podiatrist of today needs to be aware of the most important research in running shoe biomechanics in order to be able to provide the best medical advice on the most proper running shoes for their runner-patients. **PM**

References

[1] Running Boom of the 1970's. https://en.wikipedia.org/wiki/Running_boom_of_the_1970s. Retrieved 2017-06-21.

[2] http://www.emedicinehealth.com/running/article_em.htm

[3] Cavanagh PR: The Running Shoe Book. Anderson World, Inc., Mountain View, CA, 1980.

[4] Cavanagh PR, Lafortune MA: Ground reaction forces in distance running. J Biomechanics, 13, 397-406, 1980.

[5] Cheskin MP: The Complete Handbook of Athletic Footwear. Fairchild Publications, New York, 1987.

[6] Motawi W: How Shoes Are Made: A Behind the Scenes Look at a Real Shoe Factory. 3rd ed. CreateSpace Independent Publishing, USA, 2015.

[7] Nigg, B.M. (ed.). Biomechanics of Running Shoes. Human Kinetics Publishers, Inc., Champaign, Illinois, 1986.

[8] Nigg BM, Bahlsen HA, Luethi SM, Stokes S: The influence of running velocity and midsole hardness on external impact forces in heel-toe running. J Biomech, 20:951-959, 1987.

[9] Frederick EC, Hagy JL, Mann RA: Prediction of vertical impact force during running. J Biomechanics, 14:498, 1981.

[10] Clarke TE, Frederick EC, Hamill CL: The effects of shoe design parameters on rearfoot control in running. Med Sci Sports Exercise, 15:376-381, 1983.

[11] Nigg BM, Bahlsen AH: Influence of heel flare and midsole construction on pronation, supination, and impact forces for heel-toe running. Intl J Sport Biomechanics, 4(3):205-19, 1988.

[12] Nigg BM, Morlock M: The influence of lateral heel flare of running shoes on pronation and impact forces. Med Science Sports, 19:294-302, 1987.

[13] Nigg BM, Bahlsen AH, Denoth J, Luethi SM, Stacoff A: Factors influencing kinetic and kinematic variables in running. Nigg, B.M. (ed.). Biomechanics of Running Shoes. Human Kinetics Publishers, Inc., Champaign, Illinois, 1986, pp. 139-159.

[14] https://www.google.com/patents/US4364189. Accessed June 11, 2017.

[15] Blickhan R: The spring-model for running and hopping. J Biomech, 22(11/12):1217-1227, 1989.

[16] Novacheck TF: The biomechanics of running. Gait and osture, 7:77-95, 1998.

[17] McMahon TA, Greene PR: The influence of track compliance on running. J Biomech, 12:893-904, 1979.

[18] McMahon TA, Greene PR: Fast running tracks. Scientific American. 239:148-163, 1978.

[19] Frederick EC, Howley ET, Powers SK: Lower O2 cost while running in air-cushion type shoe. Med Science Sport Exerc, 12(2):81-82, 1980.

[20] Frederick EC, Sharkey BJ, Larsen JL: Running economy of elite runners wearing air-soled and non-air-soled racing flats. Unpublished report. University of Montana. 1980.

[21] Franz JR, Wierzbinski CM, Kram R: Metabolic cost of running barefoot versus shod: Is lighter better? Med Sci Sp Exerc, 44:1519-1525, 2012.

[22] Tung KD, Franz JR, Kram R: A test of the metabolic cost of cushioning hypothesis during unshod and shod running. Med Sci Sports Exerc. 46(2):324-9, 2014.

[23] Ferris DP, Liang K, Farley CT: Runners adjust leg stiffness for their first step on a new running surface. J Biomech, 32:787-794, 1999.

[24] Kerdok AE, Biewener AA, McMahon TA, Weyand PG, Herr HM: Energetics and mechanics of human running on surfaces of different stiffnesses. J Applied Physiology, 92:469-478, 2002.

[25] Hardin EC, van den Bogert AJ, Hamill J: Kinematic adaptations during running: effects of footwear, surface, and duration. Med Science Sports Exer, 36:838-844, 2004.

Dr. Kirby is an Adjunct Associate Professor in the Department of Applied Biomechanics at the California School of Podiatric Medicine and is in private practice in Sacramento, California.

CME **EXAMINATION**

See instructions and answer sheet on pages 152-154

1) Cavanagh and LaFortune, in 1980, discovered that most of their experimental subjects had what type of foot strike during running?

A) Rearfoot strike
B) Midfoot strike
C) Forefoot strike
D) Toe strike

2) Where is the midsole located in a running shoe?

A) On the most plantar aspect of the sole of the shoe
B) Within the insole, or sockliner, of the shoe
C) Between the insole and outer-sole of the shoe
D) Along the perimeter of the upper of the shoe

Continued on page 92

See instructions and answer sheet on pages 152-154

3) In Benno Nigg's 1985 experiment on running shoe midsoles, what were the research findings?
A) The drop impact test demonstrated reduced impact forces with lower durometer midsole materials.
B) The subjects experienced the least impact force when running in the lowest durometer midsoles.
C) The subjects experienced no significant increase in impact forces when running in the 35 to 55 durometer midsoles.
D) A and C.

4) Impact forces during running are increased under which following conditions?
A) Running at higher velocities.
B) Running at lower velocities.
C) With very low durometer midsoles.
D) B and C.

5) Nigg and Bahlsen discovered which of the following in their 1988 research?
A) Increased lateral rearfoot sole flare angle increased initial rearfoot pronation.
B) Decreased lateral rearfoot sole flare angle increased initial rearfoot pronation.
C) Total pronation was not affected by increased lateral rearfoot sole flare angle.
D) A and C.

6) Dual-density midsoles in running shoes, such as was patented by Bates in 1982, have which characteristics?
A) Lower durometer midsole in forefoot, higher durometer midsole in rearfoot.
B) Higher durometer midsole in medial rearfoot, lower durometer midsole in lateral rearfoot.
C) Higher durometer midsole in forefoot, lower durometer midsole in rearfoot.
D) Lower durometer midsole in medial rearfoot, higher durometer midsole in lateral rearfoot.

7) McMahon and Green, in 1979, first proposed which of the following for running?
A) Lower extremity muscles of runners will work harder on stiffer running surfaces.
B) Lower extremities of runners are like springs that have variable stiffness depending on the stiffness of the running surface.
C) Lower extremity muscles of runners will expend less metabolic energy on a stiffer running surface.
D) Lower extremities muscles of runners exhibit more eccentric contraction when running over more compliant running surfaces.

8) In 1980, research from Frederick and colleagues demonstrated which of the following?
A) Running shoes with gel midsoles reduced the metabolic cost of running.
B) Running shoes with air midsoles increase the metabolic cost of running.
C) Running shoes with gel midsoles reduced the metabolic cost of running.
D) Running shoes with air midsoles decreased the metabolic cost of running.

9) In 2012, Franz and colleagues demonstrated in their research on barefoot and shod running which of the following?
A) For equal mass added to the foot, shod running required 3-4% less metabolic energy than barefoot running.
B) There was no difference in the metabolic energy of running with mass added to the foot.
C) 100 g lead strips added to the lightweight shoes of runners required 1% less metabolic energy than no added mass.
D) For equal mass added to the foot, barefoot running required 3-4% less metabolic energy than shod running.

10) In 2014, Tung and co-workers demonstrated which of the following in their research?
A) More metabolic energy was required to run on a treadmill belt with a layer of EVA foam added than running overground.
B) Running barefoot on a 10-mm-thick EVA foam treadmill belt required more metabolic energy than running barefoot overground.
C) Running barefoot on a 10-mm-thick EVA foam treadmill belt required less metabolic energy than barefoot running on a standard treadmill belt.
D) Running on a 20-mm-thick EVA foam treadmill belt required half as much metabolic energy as running on a 10-mm-thick EVA foam treadmill belt.

SEE INSTRUCTIONS AND ANSWER SHEET ON PAGES 152-154.