# The Evolution of the Study of the Mechanics of Running

## *Relationship to Injury*

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The mechanics of running have been studied for hundreds of years. With the increase in interest in running as a recreational activity in recent years, running-related injuries have become common. Hundreds of studies on the mechanics of running have been conducted over the past few decades. However, the relationship between the mechanics of running and injury is still not well understood. This article describes the evolution of the study of the mechanics of running, with a focus on their relationship to injury. A brief historical review is presented, followed by a summary of the era of descriptive research and, finally, an overview of the more recent generation of hypothesis-driven research. The article concludes with suggestions for future research that may lead to greater insight into the relationship between lower-extremity biomechanics and injury. (J Am Podiatr Med Assoc 90(3): 133-148, 2000)

The activity of running has evolved from one that was critical to day-to-day survival to one that is considered important to overall fitness and longevity. Running has been a topic of interest for many centuries, as evidenced by its numerous artistic depictions dating back to 470 BC.[1] Over time, theoretical models and deductive postulates have paved the way to scientific inquiry. Primitive methods have given way to technologic advances. The study of running gait was further fueled by the explosion of interest in running as a recreational activity in the 1970s. This heightened interest, along with improved technologic and computational abilities of that time, generated a multitude of studies of the mechanics of running. These studies were critical to the development of an understanding of the forces and motions involved in running and serve as the foundation for all other investigations.

Another major impetus of the running research, however, was the increase in running-related injuries seen by physicians. The descriptive studies of the 1970s and 1980s were unable to provide information regarding causal relationships between running mechanics and injury. Studies of injury mechanisms were largely anecdotal and provided little insight into etiologies and preventive measures.

As a response to this, a new generation of research is emerging. These studies are hypothesis-driven rather than descriptive in nature. It is this type of research that is necessary to answer the questions that are currently being posed regarding biomechanics and injury. This article describes the evolution of the study of running mechanics in three sections: a brief historical review, a summary of the era of descriptive studies, and an overview of the current era of hypothesis-driven research. Finally, directions for future research are proposed, with the goal of enhancing the current understanding of running mechanics and their role in the etiology of injury so that optimal preventive and intervention strategies can be developed.

## A Place in History

Although early interest in running is recorded in drawings dating to the fifth century BC, the first recorded experiments related to running were con-

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ducted in the late 1800s by Wilhelm and Eduard Weber.[1] With simple instrumentation such as watches and rulers, they were able to provide some of the first spatiotemporal information collected during running. However, in 1895, Etienne Jules Marey,[2] with his affinity for instrumentation, performed some of the most technologically advanced experiments of the time. He is responsible for the development of early timing devices such as pneumatic foot switches, the first force platform, and a laboratory that allowed the measurement of running velocity. In addition, he developed photogrammetric methods using passive and active markers that were significant contributions to both the scientific (biomechanics) and cinema communities.

At approximately the same time, Braune and Fischer[3] developed a method of collecting kinematic data by attaching pulsed-electrical discharge tubes to patients whose information was then recorded on film plates. An optical device was used to digitize the coordinates of the pulsed markers, and the calculations of the three-dimensional (3-D) kinematics of the body were laboriously made by hand.

These technologic advances resulted in an abundance of new data that, in turn, facilitated the development of quantitative methods for the mechanical analysis of gait. Marey[2] used the information gained from his experiments to further his ideas regarding work and energy. Braune and Fischer[3] were the first researchers to estimate joint moments during the swing phase of gait.

Although not a scientist, Eadweard Muybridge[4] (1830–1894) contributed to the understanding of running mechanics through his creative photography. The photographic plates depicted sequential images of the running gait of humans from orthogonal viewpoints. Although little quantitative information was derived, his work consisted of the best qualitative representation of that time of the various phases of running gait.

All of these pioneers paved the way for further investigation of the biomechanics of running gait. Many of the postulates developed over a century ago are still applicable today.

## The Era of Descriptive Research

Interest in the mechanics of running was refueled with the exponential growth of running as a recreational and fitness activity in the 1960s and 1970s. Aside from some of the earlier data of Marey[2] and Braune and Fischer,[3] relatively little was known about the forces and motions that the body experiences during running.

### Kinematics

The first burst of research in the area of running mechanics was published in the late 1970s and early 1980s and was focused on the rearfoot.[5-8] Most of these data were collected with high-speed cinematography and were digitized by hand. Although it was possible to collect 3-D data with multiple cameras, the time involved in digitizing multiple camera views by hand was a significant practical limitation. Therefore, the studies during this time were two-dimensional (2-D) in nature, with the majority of studies emphasizing frontal plane motion. Markers were typically placed on the bisection of the lower third of the tibia and the bisection of the calcaneus; the angle between these bisections became known as the rearfoot angle. These investigations contributed greatly to clarifying the motion of the rearfoot (Fig. 1). Normative ranges for foot-strike position, peak eversion, and peak eversion velocities were reported. In addition, changes in these variables with speed were documented. Although it was recognized that some pronation of the foot was normal, excessive pronation was beginning to be recognized as a risk factor in running-related injuries.

Studies of rearfoot motion were further fueled by the shoe industry. The influence of running-shoe characteristics such as sole durometer and heel flare

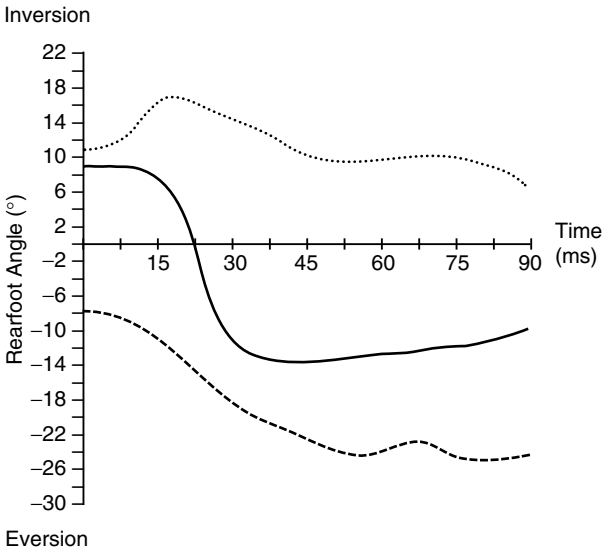


**Figure 1.** Frontal plane motion of the rearfoot for a normal runner (solid line), a runner with supination (dotted line), and a runner with excessive pronation (dashed line). (Reprinted with permission from Cavanagh.[9])

on rearfoot mechanics were studied extensively in the 1980s.[10-13] Design parameters of the running shoe have been shown to influence kinematic variables of the rearfoot such as position at foot strike, peak eversion, and peak eversion velocity. Information derived from these studies has been incorporated into the design of running shoes, which are a very different product from those of the early 1970s. All major manufacturers of running shoes now produce shoes in a variety of categories such as those classified as motion-control and cushioning shoes. Runners can now choose shoes that meet their particular needs, thereby hopefully reducing the risk of injuries. However, to date no studies have assessed the direct influence of shoes on running-related injuries.

Foot orthotic devices have been prescribed frequently for the treatment of running injuries. Studies have documented an efficacy rate of up to 75% in allowing patients to return to running with greatly reduced pain or no pain.[14-18] However, the mechanism by which these devices produce their results is not well understood. Most of the studies to date have focused on the frontal plane component of rearfoot motion.[19-22] The results thus far have been equivocal. Some studies have reported small but significant reductions in peak eversion, with greater reductions in eversion velocity. However, other studies have reported no significant kinematic differences with orthotic intervention. These discrepancies may be attributed in part to variations in orthotic design, materials, and posting. In addition, the effect being measured may be at too subtle a level to be measured with the means currently available.

Although foot orthotic devices are very often prescribed for knee-related injuries, few studies have ventured beyond the rearfoot. Cornwall and McPoil[23] used a tibial pointer device and reported less than a 1° reduction in tibial rotation as a result of orthotic intervention in two cases. McClay et al[24] used an intracortical pin protocol and a 6-*df* biomechanical model and reported changes in both tibiofemoral and patellofemoral joint kinematics in two patients exhibiting excessive pronation and patellofemoral joint pain. Both subjects were able to run with reduced pain as a result of the orthotic devices; however, their mechanical responses to the identically prescribed orthoses were quite different (Fig. 2).

Although the rearfoot has been the focus of most studies of running injuries, some studies have concentrated on the sagittal plane motion of the ankle, knee, and hip joints (Fig. 3). One of the early biomechanical studies of running was conducted by Sinning and Forsyth in 1970.[25] These scientists used electrogoniometers and were able to record the motions of the ankle, knee, and hip over eight speeds ranging from 183 to 396 m/min. Fifteen years later, Nilsson et al[26] conducted a similar study using cinematography and obtained corresponding results. In general, it has been noted that as speed increases, joints move through greater ranges of motion in shorter time periods, resulting in higher angular velocities.

Cavanagh[9] introduced the use of angle-angle diagrams into the running mechanics literature. These

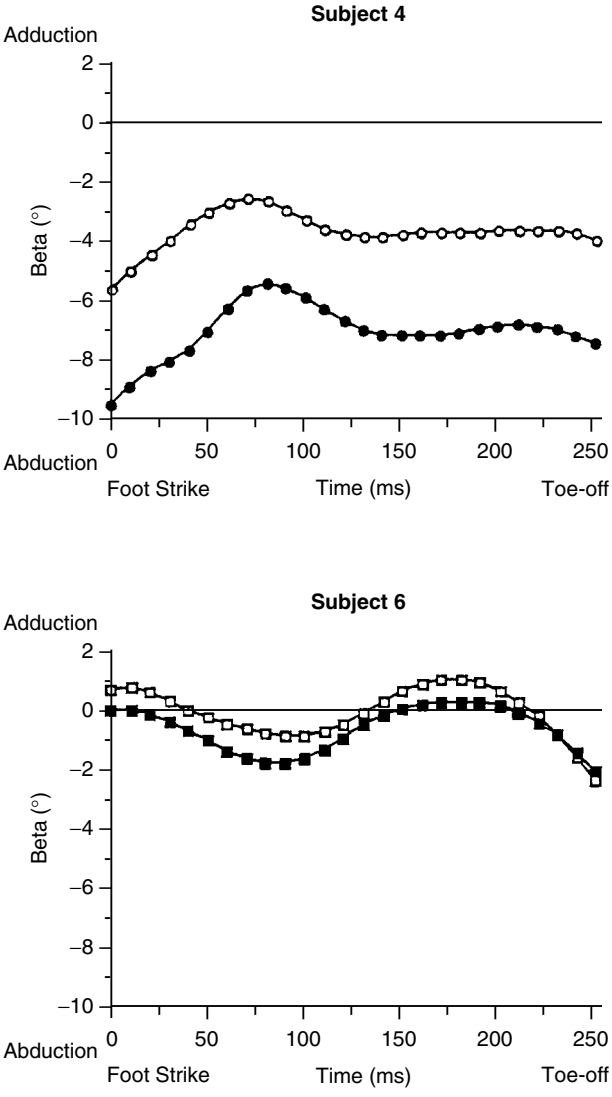


**Figure 2.** Changes in frontal plane rotation of the patella in two runners as a result of orthotic intervention. The open symbols represent the condition without orthoses and the closed symbols represent the condition with orthoses. Note the difference in response between the two subjects.

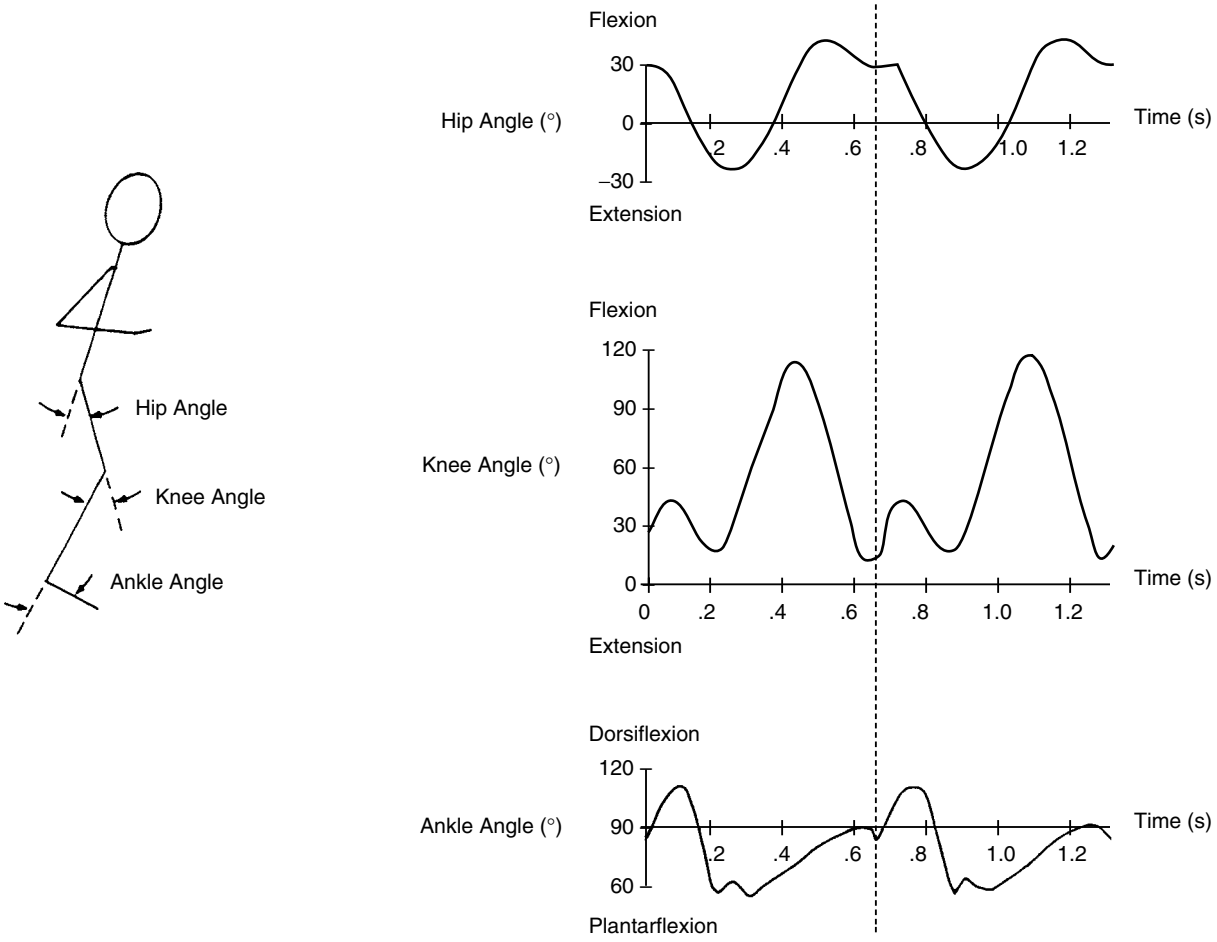


**Figure 3.** Sagittal plane kinematics of the ankle, knee, and hip over two complete strides. Foot strike occurs at time = 0 and coincident with the dashed line. (Reprinted with permission from Cavanagh.[9])

diagrams have the element of time removed; however, they allow one to assess the coordination of movement between two joints. For example, when the trajectory is parallel to an axis, movement is occurring at only one joint; when the trajectory is at a 45° orientation, equal motion is occurring at both joints. In addition, a qualitative assessment of the shape (width and height) of the diagram can provide insight into differences between subjects, between conditions, and potentially between injured and noninjured states (Fig. 4).

## Ground-Reaction Forces

The study of ground-reaction forces has enabled an understanding of the forces that create motion. The early studies of ground-reaction forces provided the characteristic tracings of vertical, anteroposterior, and mediolateral components shown in Figure 5.[27-29] Most running research has been done on subjects who strike the ground first with the heel (rearfoot strikers), but Cavanagh and Lafortune[27] were among the first researchers to recognize the differences between rearfoot strikers and those who strike the ground first with the ball of the foot (forefoot strikers). They noted that the impact peak of the vertical ground-reaction force curve was attenuated or missing in forefoot strikers (Fig. 5). In addition, the braking phase of the anteroposterior ground-reaction force had a biphasic pattern. This is associated with the backward movement of the center of pressure as the heel drops, followed by an anterior movement as the center of mass progresses forward over the foot.

The rate at which forces are applied to the body has also been studied. Vertical loading rates for running have been reported in the literature[30] and sug-

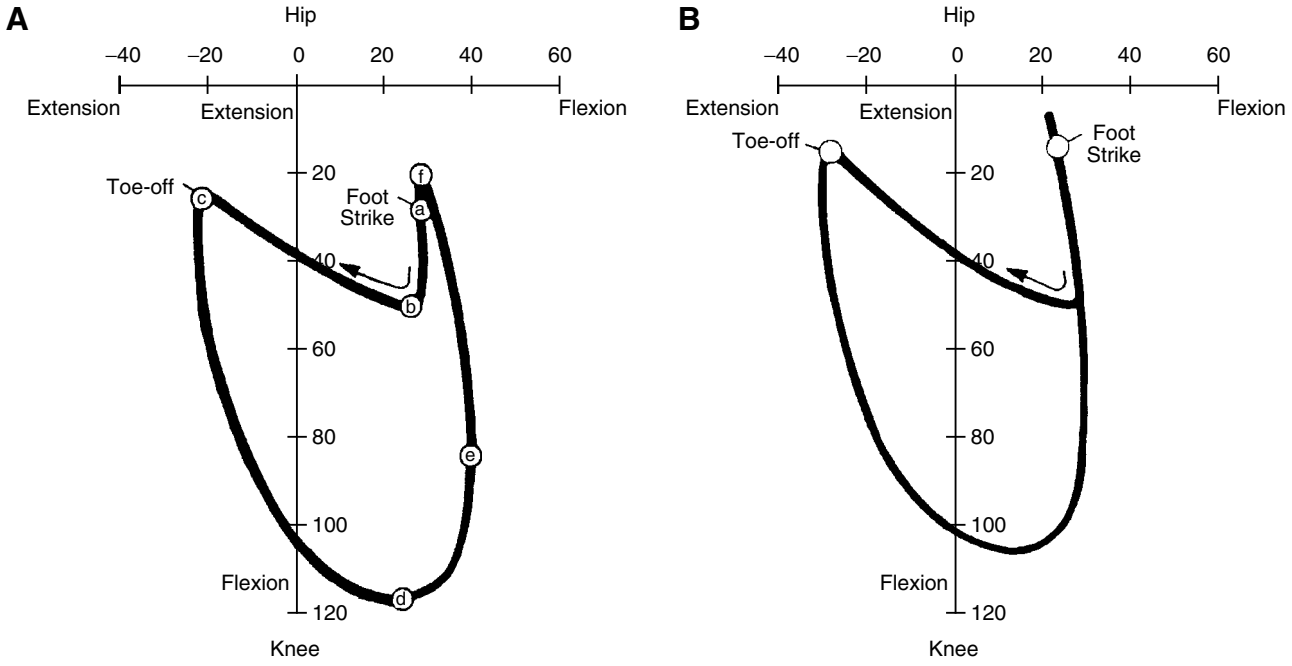


**Figure 4 A and B.** Angle-angle diagrams of the hip and knee during one complete stride of running for two runners. Note the difference in shape of these diagrams between the two subjects. a, Foot strike; b-c, propulsive phase; c, toe-off; d, maximum knee flexion; e, maximum hip flexion; f, maximum knee extension. (Reprinted with permission from Cavanagh.[9])

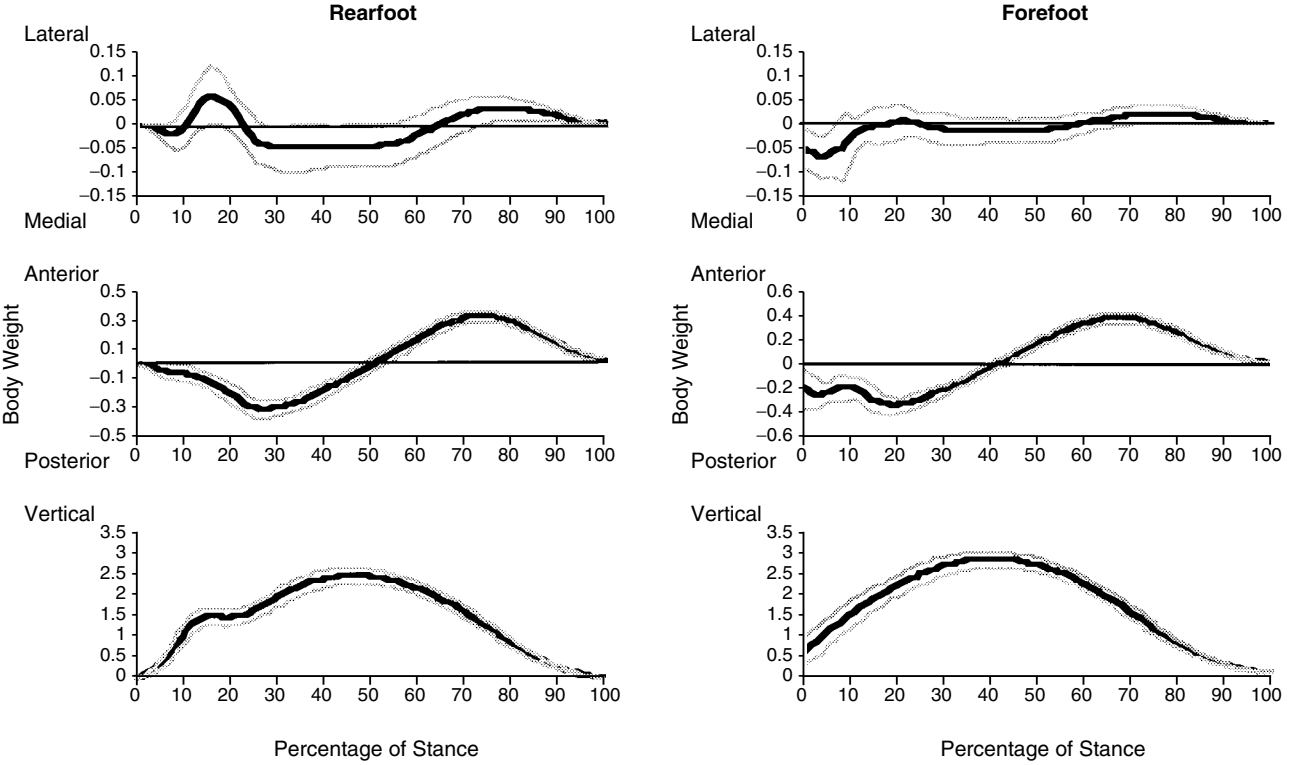


**Figure 5.** Mediolateral (top panel), anteroposterior (middle panel), and vertical (bottom panel) ground-reaction force profiles of a runner who makes initial contact with the ground with the heel (rearfoot) compared with a runner who strikes the ground with the ball of the foot (forefoot). The thin lines represent ±1 SD. Note the characteristic missing vertical impact peak and the biphasic pattern to the braking force of the forefoot striker.

gestions made with regard to injury[31]; however, correlations to specific injuries have not been systematically assessed. Although ground-reaction forces are thought to play a role in running injuries, it is still unknown whether it is peak forces, loading rate, number of repetitions, or some combination of factors that places a runner at risk.

### Joint Kinetics

The study of angular joint kinetics is important because it provides insight into the function of muscles involved during running. An estimation of the internal muscle moments that cause joint motion may be obtained through inverse dynamics using the combination of kinematic and ground-reaction force data. Although it is muscle forces that cause the body to accelerate (force equals mass times acceleration), these muscle forces are difficult to measure directly. However, the acceleration of the body can be measured by recording the movement patterns of the body during motion. Because acceleration is measured and forces and moments are derived mathematically, the process is called inverse dynamics. The sagittal plane moments of the ankle, knee, and hip during running have been described by a number of researchers; representative patterns of these moments are demonstrated in Figure 6.[32-36] Moments alone do not provide information about the manner in which the muscle is functioning. Joint power can be determined by multiplying joint moment by angular velocity. The amount of eccentric and concentric work done during running can be derived by calculating the area under the respective negative and positive portions of the power curve. The clinical significance of these kinetic variables is still not well understood.

### Electromyography

Without information about exactly which muscles are active and when, calculated joint moments must be interpreted cautiously. For example, an extension moment that is calculated at the knee may be the result of the extensor muscles acting alone or having greater activity than the flexor muscles. Electromyography (EMG) helps to improve the interpretation of these data. The majority of studies investigating EMG during running have used surface electrodes.[26, 37-39] A discussion of surface *versus* indwelling electrode techniques is beyond the scope of this article. However, surface electrodes only allow monitoring of musculature close to the surface of the skin. These EMG studies have provided information regarding the primary musculature of the hip, knee, and ankle joints during running. Understanding abnormalities in muscle firing may provide insight into the neuromuscular factors related to injury.

### Accelerometry

The impact force of contact during running results in a transient shock, which is transmitted and attenuated through the musculoskeletal system of the body,

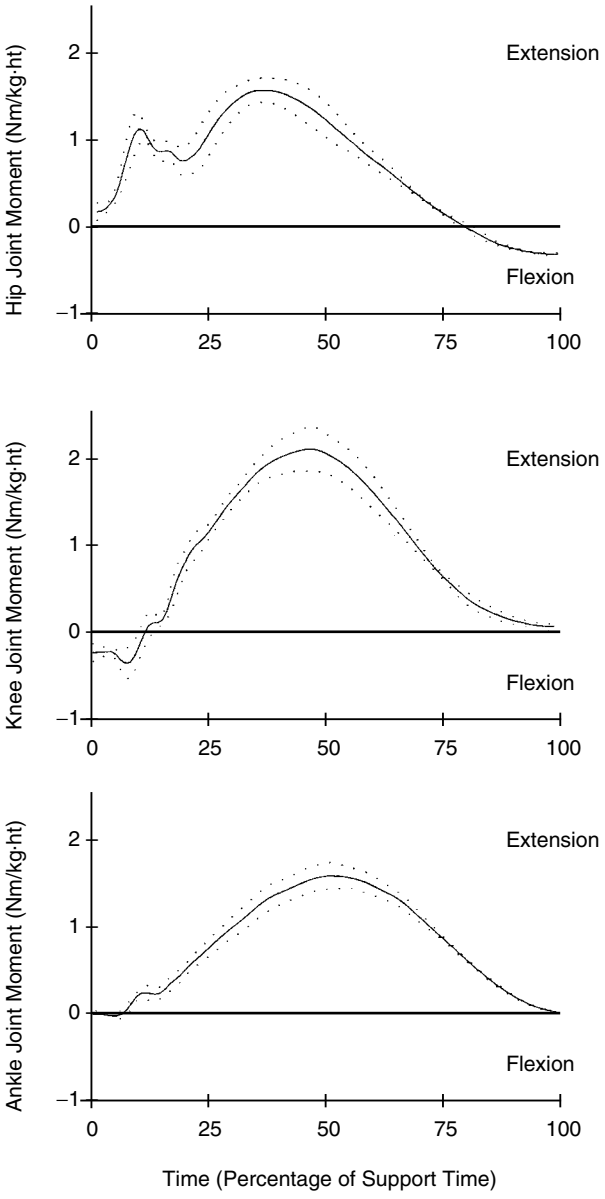


**Figure 6.** Sagittal plane kinetics of the ankle, knee, and hip joint during the contact phase of running. The dotted lines represent ±1 SD. (Reprinted with permission from Simpson and Bates.[36])

resulting in significant reductions in the magnitude of the shock wave as it reaches the head.[40] It is the lower extremity that bears the brunt of the impact. It has been shown that the shock experienced by the head is fairly constant regardless of running speed, suggesting that greater shock attenuation must occur throughout the body at higher speeds, which may place the musculoskeletal system at greater risk of injury.

Although relationships between peak tibial acceleration and loading rates of ground-reaction forces have been found, peak accelerations were not found to be correlated with runners' weights.[41] In animal studies, repetitive impulse loading of joints has led to the development of degenerative osteoarthritis.[42] However, it has yet to be shown that high accelerations lead to injury in humans.

### Epidemiologic Studies

Numerous epidemiologic studies have been conducted that classify the injuries that runners sustain by type (ie, sprains, strains, fractures) and location.[43-46] The knee is by far the most common site of running-related injuries, followed by the lower leg and the foot. Patellofemoral pain syndrome is the most common diagnosis in running-related injuries, with tibial stress syndromes and muscular tendinitis following close behind.

A review of epidemiologic studies by van Mechelen[47] concludes that the annual incidence of running injuries is between 37% and 56%. Approximately 50% to 75% of injuries are overuse in nature, and recurrence of injury is reported in 20% to 70% of the cases. The weekly amount of running is considered a strong determining factor in injury, with risk increasing with both the duration and the frequency of running. However, the optimal combination of duration and frequency for a given weekly mileage is not known. Marti et al[48] found no differences in the incidence of injuries in runners with similar weekly distances but different numbers of weekly sessions.

## The New Generation of Research

With the advent of automated motion-analysis systems, the problems associated with obtaining 3-D data have been greatly alleviated. This has expanded the ability to assess all of the components of the mechanics related to a subject's running. Many of the abnormalities in running mechanics that are thought to be associated with injury occur in the secondary planes of motion. For example, excessive pronation has been suggested to result in genu valgum (knock-knee) and internal rotation of the knee. It is hoped that examining these components will yield greater insight into running-related injuries. However, it must be recognized that measurement of movement in the secondary planes of motion is much more sensitive to errors caused from soft-tissue movement and misalignment of markers.[49] Until these problems can be overcome, these components of motion must be interpreted with caution.

Researchers studying running-related injuries are also beginning to examine the coordination of movement between various joints of the lower extremity rather than viewing joints in isolation. The timing of movements of adjacent joints and the variability in the coupling of motion are topics that are currently being examined. Finally, more hypothesis-driven research is being reported in the literature. The descriptive studies of the past have served as the basis for the questions that are currently being addressed.

### Three-Dimensional Kinematics

Aside from presenting an incomplete picture of the biomechanics of a runner, a 2-D approach is prone to errors of perspective unless the anatomical plane of interest is oriented exactly perpendicular to the optical axis of the camera. Soutas-Little et al[50] mathematically estimated an error rate of up to 40% when a segment's plane is inclined 9° from the projected plane. This is most likely to occur in the foot if there is excessive out-toeing or during plantarflexion, which takes place during the late stance phase. Areblad et al[51] examined the effects of altering a rear-camera placement on the calculation of the 2-D rearfoot angle during running. They increased the angle between the optical axis of the camera and the frontal plane of the laboratory coordinate system a total of 40° in 5° increments. Some variables changed as much as 1° for every 2° of angular alignment change.

Rather than altering camera placement, McClay and Manal[52] assessed the influence of natural foot abduction on the difference between 2-D and 3-D measurements. Their findings suggested that 2-D and 3-D eversion differences increase significantly as out-toeing, defined as the angle between the longitudinal axis of the foot and the direction of progression during walking, exceeds 20°.

These investigations provide evidence of the need for a 3-D approach to the study of running mechanics, and introduce some of the first 3-D rearfoot motion data into the running literature. To understand the mechanics of injury, normative values for secondary planes of motion need to be established. It

should be noted that because the markers are placed on the calcaneus and tibia, the motion that is measured is occurring across two joints, the subtalar and talocrural joints. It is assumed that the majority of sagittal plane motion is occurring at the talocrural joint and most of the transverse and frontal plane motion takes place at the subtalar joint. This assumption is supported by the work of Lundberg.[53] He implanted tantalum balls into many of the bones of the foot and calculated rigid-body kinematics of the subtalar, talocrural, talonavicular, and calcaneocuboid joints as the foot and lower extremity were moved through a range of motion in the weightbearing position. His work suggested that, through the ranges of motion that are typical for running gait, little motion occurs at the talocrural joint in the transverse and frontal planes.

Figure 7 demonstrates the three components of the rearfoot during the stance phase of running in a group of runners with excessive eversion compared with those with a normal range of eversion.[45] The general pattern for both groups is dorsiflexion, eversion, and abduction for the first half of stance, followed by plantarflexion, inversion, and adduction in the second half of stance. Note that the subjects with excessive eversion land in an everted position and exhibit twice the peak eversion of runners who have a normal range of eversion. Peak eversion and dorsiflexion velocities were higher in the runners with excessive eversion.

The 3-D pattern of knee motion in these same runners is shown in Figure 8. In general, the knee flexes, adducts, and rotates internally during the first half of stance, with extension, abduction, and external rotation during the last half. The kinematic differences at the knee were smaller than those seen at the rearfoot between the two groups. The subjects with excessive eversion exhibited significantly greater peak knee flexion and lesser peak knee adduction and adduction excursion, suggesting a relatively more valgus position of the knee. In addition, peak knee flexion velocity was higher in the group of runners with excessive eversion.

The incidence of running-related injuries was also assessed in this study and was found to be higher in the subjects with excessive eversion compared with their normal counterparts. Sixty-seven percent (six of nine) of the subjects with excessive eversion reported injuries that included patellar tendinitis, Achilles tendinitis, shin splints, knee ligament damage, and ankle sprains. Only 22% (two of nine) of the normal subjects sustained injuries, which included iliotibial band syndrome and an inguinal hernia (perhaps unrelated to running). However, no distinct distribution of injuries could be identified in the study because of the small sample size.

Interestingly, patellar tendinitis, posterior tibial tendinitis, and Achilles tendinitis are among the ten most common running injuries cited by Clement et al[45] in their study of 1,650 patients. In the study by

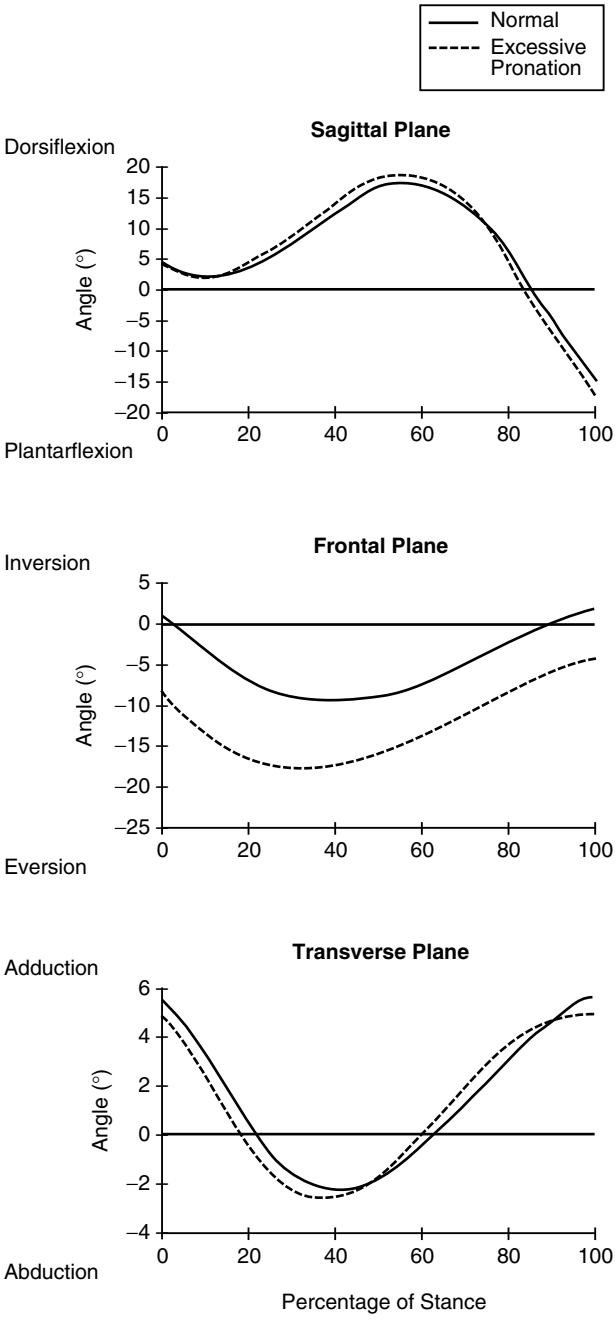


**Figure 7.** A comparison of 3-D kinematics of the rearfoot in runners with normal rearfoot mechanics and those with excessive pronation.

McClay and Manal,[52] the subject who reported having patellar tendinitis displayed one of the highest peak knee flexion velocities of the group of runners with excessive eversion. Similarly, one of the highest peak dorsiflexion velocities of this group was noted in a subject who had a history of Achilles tendinitis. However, studies of a much larger scale are needed to examine some of the injury mechanisms proposed here.

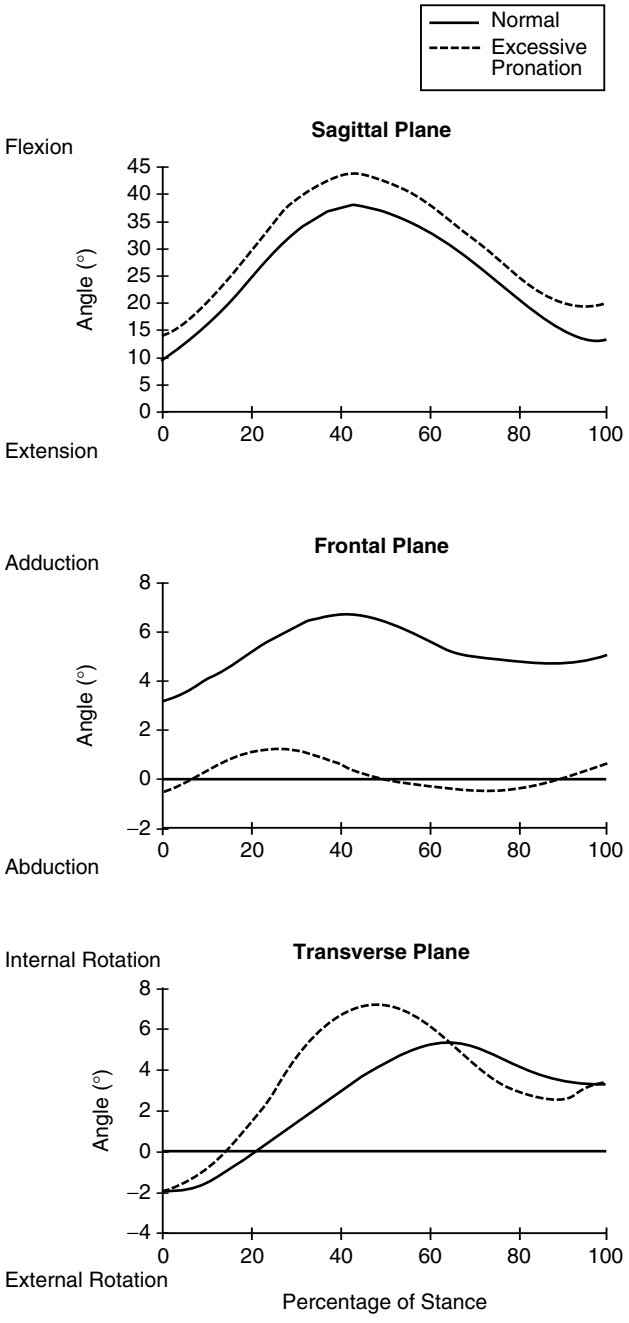


**Figure 8.** A comparison of 3-D kinematics of the knee in runners with normal rearfoot mechanics and those with excessive pronation.

## Three-Dimensional Kinetics

Until recently, little has been known about lower-extremity joint kinetics in the secondary planes of motion. However, many of the proposed mechanisms of running injuries occur in the frontal and transverse planes. For example, excessive genu varum may place abnormal demands on the lateral structures of the knee, such as the iliotibial band and lateral hamstrings, forcing them to respond with increased internal valgus moments. In addition, it has been hypothesized that increased inversion moments may be associated with excessive rearfoot pronation as tibialis posterior attempts to control the motion.

McClay and Manal[54] have reported on 3-D kinetics of the rearfoot and knee during running. Results of this investigation are shown in Figure 9. The results suggest that a significant amount of work is done in the frontal and transverse planes of motion. Transverse plane motion exhibited the greatest amount of between-subject variability. Therefore, as noted earlier, kinetics in this plane of motion must be interpreted with caution.

## Strike Patterns

The focus of almost all running studies to date has been on rearfoot strikers because they have been reported to constitute 80% of distance runners.[55] Except for the ground-reaction force studies of Cavanagh and Lafortune,[27] very little is known about the biomechanics of runners who strike on the balls of their feet. Interest in this topic was sparked by a runner who presented to the author with an unusual injury history. He was originally a rearfoot striker who developed a tibial stress fracture. Rather than discontinue running, he adopted a forefoot strike pattern that resolved his stress fracture but resulted in Achilles tendinitis. He continued to vacillate between strike patterns, trading one injury for the other. This provides evidence for the hypothesis that different mechanics place one at risk for different types of injuries.

McClay and Manal[56, 57] compared the lower-extremity mechanics of ten rearfoot strikers with those of ten forefoot strikers. Significant differences were found in both kinematics and kinetics. At the rearfoot, the forefoot strikers landed in greater plantarflexion and inversion. However, peak dorsiflexion and eversion were similar in the two groups, resulting in higher dorsiflexion and eversion excursions in the forefoot striker group. The larger excursions

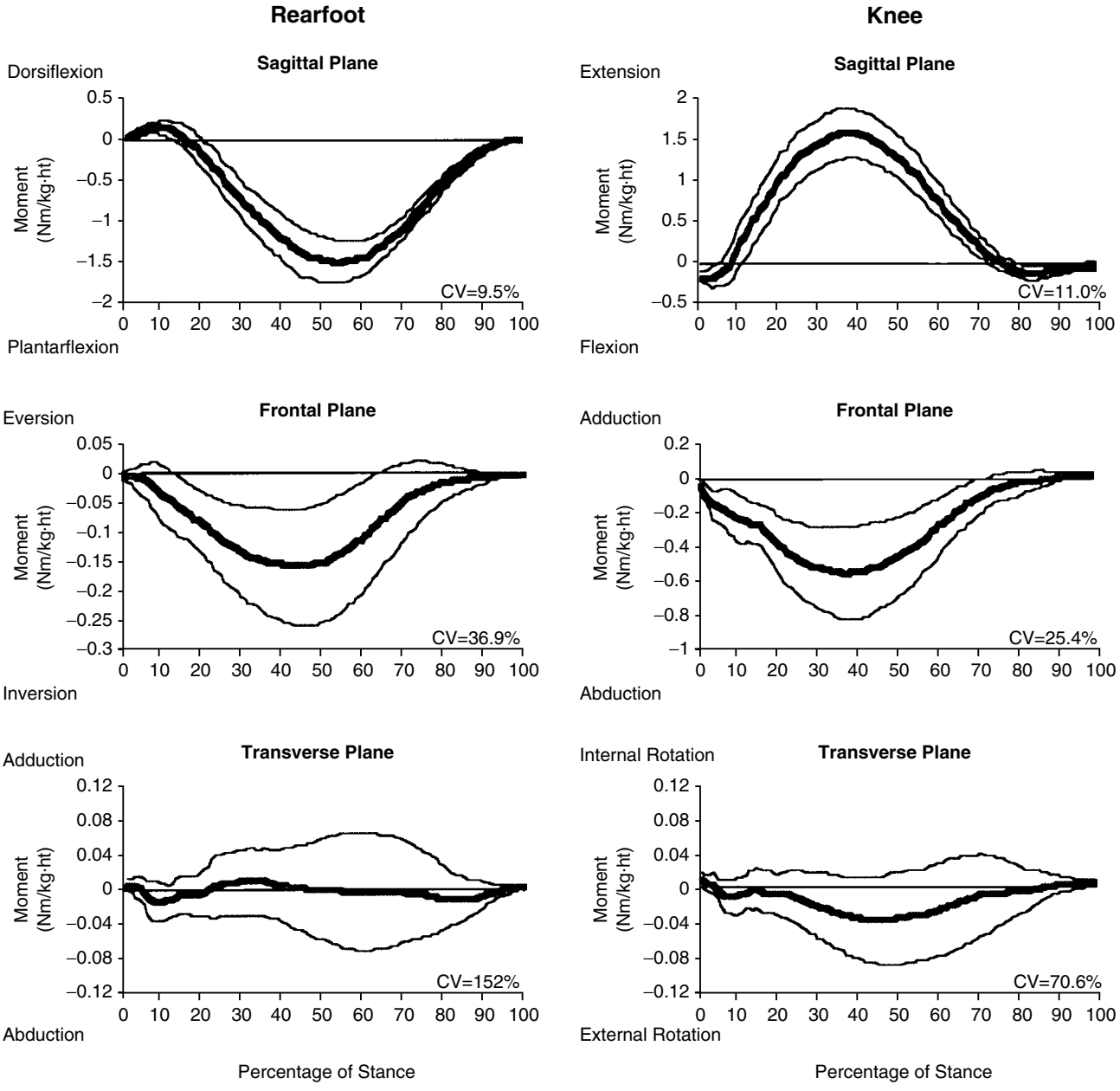


**Figure 9.** Three-dimensional components of the calculated net moment at the rearfoot and knee during running. The thin lines represent ±1 SD. CV, coefficient of variation.

occurred in similar time frames and resulted in significantly higher eversion and dorsiflexion velocities in the forefoot striker group. Peak plantarflexion moment and power were greater in the forefoot strikers, with greater negative work done by the plantar flexors (Fig. 10). This, along with the higher dorsiflexion velocities, is likely to place greater demands on the calf musculature and may be related to the Achilles tendinitis injury the previously mentioned runner experienced when running with a forefoot striker pattern.

Forefoot strikers land in greater flexion and external rotation at the knee. Internal rotation velocities were higher in this group; however, knee flexion excursions and velocities were lower. Peak knee extension moments were similar between the two groups, but power absorption and negative work were lower in the forefoot strikers (Fig. 10). This finding may suggest that a forefoot striker pattern places lower

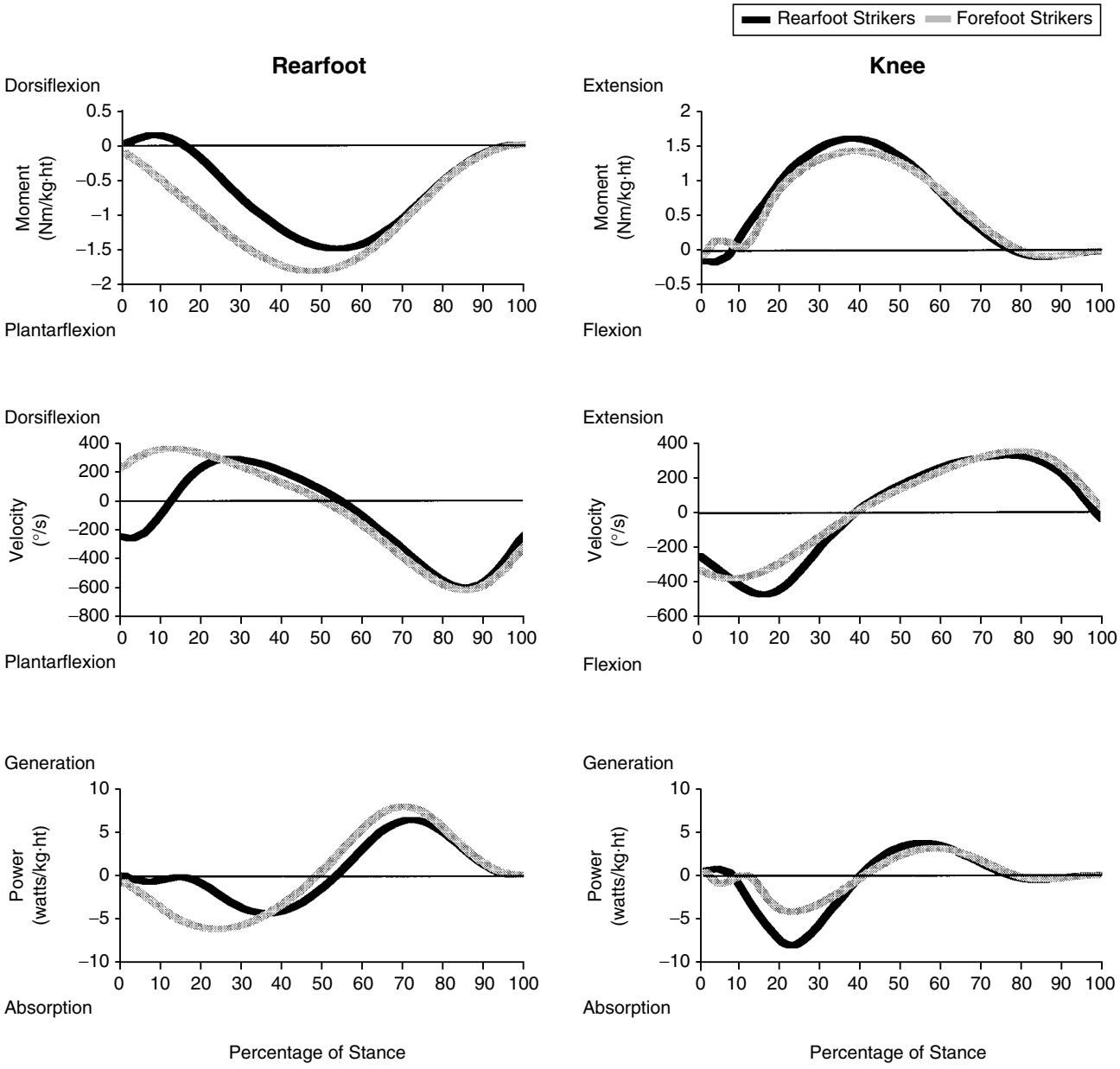


**Figure 10.** A comparison of sagittal plane moment, velocity, and power curves for the rearfoot and the knee for runners who make initial contact with the ground with their heel (rearfoot strikers) and those who strike first on the ball of the foot (forefoot strikers).

demands on the quadriceps musculature and might be a preferred strike pattern for runners with knee-related problems. In addition, vertical loading rates were reduced by 50% in the forefoot striker group. Hennig et al[41] reported a strong correlation between vertical loading rates and shock transmitted to the tibia in rearfoot strikers. If this same relationship holds true for forefoot strikers, reducing the vertical loading rates may decrease the risk of impact-related injuries such as tibial stress fractures. However, much more research in this area is needed before these types of conclusions can be drawn.

## Coupling

The focus of running studies to date has been on the action of lower-extremity joints individually rather than the interaction among these joints. Qualitative

assessments of relationships between joints have been performed through visual observation of angle-angle diagrams of sagittal plane motion between the hip and knee or the ankle and knee.[9] However, few studies have examined quantitative variables of foot-knee coupling during running. Bates et al[5] were among the first researchers to suggest that a disruption in the coordination of movement between the rearfoot and the knee may result in injury.

For example, excessive subtalar joint pronation is often associated with knee problems,[5] yet the effect of excessive rearfoot motion on knee mechanics remains unknown. The rearfoot and the knee are linked mechanically through the subtalar joint. Thus motions at the foot will influence movements of the knee. During closed-chain pronation, the talus, and consequently the tibia, internally rotate as the calcaneus everts.[53] Excessive pronation is thought to lead to excessive internal rotation of the knee.[5] This has the potential to cause increased strain on the soft tissues of the knee or increase the torsional loads within the tibia itself. The transfer of frontal plane movement of the foot (through calcaneal motion) to transverse plane movement at the knee (through tibial motion) occurs through the subtalar joint.

The subtalar joint axis is reported to be inclined in the sagittal plane approximately 45° from the bottom surface of the foot.[58, 59] Thus it is midway between the frontal and transverse planes of the body. Consequently, in theory, there should be equal amounts of calcaneal eversion and tibial internal rotation excursions during rearfoot pronation. This would result in a normal calcaneal eversion/tibial internal rotation excursion ratio of approximately 1:0. Lundberg[53] reported a mean subtalar joint inclination angle of 32°. Although this value is significantly lower than that reported earlier,[58, 59] it may be a more valid measure. The research of Lundberg[53] was performed on live subjects, as opposed to the cadaveric work of the previous reports. If further *in vivo* studies support the finding of a smaller subtalar joint inclination angle, then normal eversion/tibial internal rotation ratios would be expected to be greater than 1:0. One may speculate that, in relation to normal values, higher ratios (greater relative eversion) may predispose a runner to more foot-related injuries, while lower ratios (greater relative tibial internal rotation) may place a runner at greater risk for knee-related injuries. This assumes equal femoral rotation in both cases.

Nigg et al[60] examined the relationship between arch structure and the eversion/tibial internal rotation excursion ratio. Their study was based on the premise that a lower arch would be associated with a less inclined subtalar joint axis and, consequently, greater relative eversion, resulting in higher eversion/tibial internal rotation ratios. Surprisingly, eversion excursions in the groups with high and low arches were similar. However, tibial internal rotation excursions were lower in the group with low arches, resulting in a higher eversion/tibial internal rotation ratio for these subjects. The average ratio reported in their study was 1:32.

In a similar study, Nawoczenski et al[61] assessed the eversion/tibial internal rotation ratio in two groups of asymptomatic runners. Subjects were prescreened radiographically, and those who met specific criteria were placed into a high- or low-arched group. These researchers assessed the coupling during the first half of stance, during which eversion and tibial internal rotation were occurring, and assessed the coupling between total calcaneal and tibial excursions throughout stance. In both cases, the subjects in the low-arch group exhibited more calcaneal motion relative to tibial motion; however, only the total excursion ratio was significant. Higher ratios were due to similar eversion excursions between the groups; however, the subjects in the low-arch group demonstrated lower tibial excursions.

McClay and Manal[62] examined this ratio in two groups of runners. The eversion/tibial internal rotation ratio (during the first half of stance) was compared in ten subjects with excessive peak eversion (mean, 21.1°) and ten subjects with normal peak eversion (mean, 11.1°). They found significantly lower eversion/tibial internal rotation ratios in the group with excessive pronation compared with the normal subjects. Again, eversion excursions were similar in the two groups; however, the subjects with excessive pronation exhibited significantly greater tibial internal rotation excursions. This was suggested as a possible factor in the frequency with which knee problems are seen in runners with excessive rearfoot pronation.

Hamill et al[63] were interested in assessing the coupling that occurs continuously throughout the stance phase of running. Recognizing that this coupling probably changes throughout the stance phase, these investigators chose to use a dynamic systems approach to study the coordination between the rearfoot and knee. They calculated relative phase angles for coupling between the following segments of the lower extremity: femoral flexion/extension and tibial internal/external rotation, femoral abduction/adduction and tibial internal/external rotation, and foot eversion/inversion and tibial internal/external rotation. When comparing the variability of these continuous relative-phase angles, they found significantly lower variability in patients with patellofemoral joint pain compared with asymptomatic runners. On the basis

of these data, these authors suggest that decreased variability in the coupling of motion may be a contributing factor in overuse injuries in runners.

Another means of exploring the joint coupling is to investigate the relative timing, or synchrony, of motion between two joints. Tibial internal rotation is associated with flexion at the knee joint and eversion at the rearfoot, and it has been proposed that these motions should be synchronous[5, 64]; that is, peak knee flexion and internal rotation would occur at approximately the same time as peak subtalar joint pronation, resulting in both joints reversing their motions together. Problems may result, for example, if eversion is prolonged and extends into the period of knee extension. As the rearfoot everts, the talus, and consequently the tibia, rotate internally. However, tibial external rotation is associated with knee extension. Therefore, torsional stresses at the knee joint or within the tibia may result. Bates et al[65] found no significant difference between time of peak knee flexion and peak eversion in either runners with normal mechanics or those with pronation. However, the mean peak eversion value of the group with pronation was only 11°, which is well within the range of 8° to 15° reported for normal runners.[6]

Hamill et al[64] studied the effect of three midsole durometers on relative timing of peak knee flexion and eversion. They found that the softest midsole resulted in the greatest rearfoot eversion. In addition, the relative timing between peak knee flexion and peak rearfoot eversion was increased with the softest midsole, with eversion occurring first. Van Woensel and Cavanagh[66] reported on the influence of shoes designed to produce varus and valgus conditions on the timing of eversion and flexion. They reported that the time between these events was significantly increased for both the varus- and valgus-producing shoes, as compared with the neutral shoe condition. These two studies compared mean times to peak eversion and peak knee flexion rather than assessing the individual relative times and then averaging across the conditions. This method has the potential to mask individual differences in the relative timing.

In a more recent study, McClay and Manal[62] reported that times of peak eversion and tibial internal rotation were more closely matched in runners with normal rearfoot mechanics as compared with runners with excessive pronation. With only five subjects per group, lack of power limited the ability to draw statistical conclusions from these data. Future studies involving larger numbers of subjects are needed to further compare these timing parameters in groups of runners with either specific injuries or mechanical abnormalities.

### Structure and Injury Studies

An individual's mechanics are dictated, in part, by his or her anatomical structure and alignment. Because aberrant mechanics are thought to lead to injury, a number of attempts have been made to predict injury on the basis of a runner's anatomical structure. However, the results of these studies have been equivocal. Warren and Jones,[67] using measures such as leg length, subtalar joint pronation, ankle plantarflexion and dorsiflexion range, and arch height, were unable to correctly predict the incidence of plantar fasciitis. In another study, no direct association was found between selected structural measures of the lower extremity and tibial stress fractures.[68] However, it has been found that feet with high arches are more likely to sustain stress fractures of the lower extremity than feet with low arches.[69, 70] Another study indicated that soldiers with forefoot varus and decreased dorsiflexion had significantly increased odds of developing metatarsal stress fractures.[71] Yet another investigation revealed a significant relationship between the Q angle and patellofemoral joint pain.[72]

A study by McCaw[73] suggested that a significant leg-length discrepancy results in higher loading on the longer leg, perhaps placing it at greater risk of injury. Therefore, a number of studies have investigated the association of leg-length discrepancy and injury in runners. Some of these studies have found associations between leg-length discrepancy and injury,[45, 74-76] but others have not.[72, 77] Some of these studies are self-reported surveys.[45, 74, 75] In addition, discrepancies in results may be partly due to differences in criteria used to define leg-length discrepancy.

These studies seem to point to a relationship between anatomical structure and injury. However, efforts to define more accurately the criteria for abnormal structure are necessary. In addition, more investigations of the relationship between structure and mechanics, such as that by McCaw,[73] are needed to further substantiate the role played by aberrant anatomical structure in biomechanics and injury.

## Future Research Directions

The importance of physical activity as a means of maintaining health and overall productivity is being recognized by insurance companies and federal funding agencies. Research dollars are now being allocated to the study of ways of maintaining overall fitness to combat risks to cardiovascular, musculoskeletal, and psychological health. Because running is one of the most popular fitness activities, minimizing injuries in runners should have a significant impact on

some health-care costs. Therefore, the current movement toward hypothesis-driven research needs to continue and build on the knowledge that has been gained in the past few decades.

It is recognized that the factors that have been examined seldom are involved in simple one-to-one relationships. Running injuries are likely to be multifactorial in nature, involving structural, biomechanical, and training factors. For example, a runner with excessive pronation may not have a problem unless, along with the abnormal mechanics, he or she also exhibits genu valgum and runs 60 miles per week. Therefore, multifactorial models must be generated to more optimally predict who is at risk for injury.

One of the problems in studying the mechanics of an injured runner is that of determining whether the mechanics are a result or a cause of the runner's injury. Cross-sectional studies only allow clinicians to establish relationships. Longitudinal, prospective studies, although expensive and difficult to perform, are needed to determine cause and effect.

To date, the majority of studies on runners have been performed on normal, uninjured runners. The results of these studies have been extrapolated to other populations of runners. To gain a greater understanding of the etiology of running-related injuries, more studies are needed that focus on the mechanics of runners with specific injuries or specific pathomechanics. For example, it has yet to be established whether runners with higher eversion/tibial internal rotation ratios have a higher rate of foot injuries and those with lower ratios are more prone to knee injuries, as is often postulated. Further study of the role of variability of lower-extremity mechanics in injury is also warranted.

The study of injury mechanics in runners is in its infancy. Researchers are still in the process of determining which of the mechanical factors are associated with specific injuries. For example, are stress fractures more closely linked to high forces, high loading rates, the number of repetitions, or some combination of these factors? Once the factors are identified, the next generation of research will be aimed at developing strategies to alter an individual's biomechanics through techniques such as biofeedback and gait retraining.

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