RUNNING SHOE DESIGN: PROTECTION AND PERFORMANCE

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ABSTRACT

The overuse injuries commonly experienced by runners can be attributed to a number of risk factors. The primary risk factor is repetitive impact loading of the lower extremity, but anatomical predispositions, excessive subtalar joint pronation, running surfaces, shoes and training habits all contribute to the probability of injury.

Running shoes are rarely the sole cause of an injury and equally rarely are they a panacea. However, appropriately designed shoes can reduce injury risk by moderating the effects of repeated impacts and excessive pronation. Cushioned soles redistribute the loads on the foot, reduce peak pressures on the plantar surface of the foot and attenuate the impact shock wave transmitted to the skeleton. Similarly, design features such as varus wedges, variable density cushioning systems and mechanical stiffening elements can be used to control subtalar joint pronation. Such features directly intervene in the putative mechanisms of patello-femoral pain, Achilles tendonitis, stress fractures and other lower extremity injuries.

It is commonly believed that wearing lighter shoes with fewer protective features can save energy. While oxygen uptake my be reduced by 1% or so for every 100 grammes of shoe weight saved, the runner’s kinematic adaptations to reduced cushioning has been found to produce a similar increase in oxygen consumption. Therefore, most runners have little to gain by selecting shoes that lack risk-reducing features.

KEYWORDS

Running shoes, Running injuries, Cushioning, Stability, Pronation

INTRODUCTION

During the course of a marathon race, the runner experiences approximately 25000 impacts with the ground. The repeated impact loading of the body during running is a factor in the development of overuse injuries, and has been directly implicated in the aetiology of lower extremity stress fractures, shin splints and low back pain. Many common running injuries are associated with secondary effects, however: the rapid joint motions, soft tissue stresses and muscle forces induced by impact between the foot and the surface. Injuries of this latter type include common knee pain syndromes, Achilles tendinitis and plantar fasciitis.

The evolution of athletic shoes has shadowed that of the surfaces on which athletes perform. In ancient Greece, Olympians competed barefoot on clay surfaces dusted with sand. We can surmise that Pheidippides, the first marathoner of legend, ran across natural surfaces either barefoot or wearing the leather sandals in common use at the time. Running shoes with protective features are a relatively recent invention, paralleling development of distance running on hard roads as a popular activity. Although Abebe Bikila ran barefoot to victory in the 1960 Olympic marathon, most modern runners prefer, like Bikila in his 1964 win, to wear shoes.

As the primary interface between the runner and the road, the shoe has a potentially important role to play in the management of repetitive impact loads. Over the past twenty years, running shoes designs have changed significantly. The purpose of this paper is to explore how our changing understanding of running injury mechanisms and lower extremity biomechanics have been reflected in changing running shoe designs.

SURVEYS OF RUNNING INJURIES AND RUNNING SHOES *circa* 1980

Prior to 1978, relatively little was know of the frequency or cause of overuse injuries among runners. Surveys conducted by the Runner's World Magazine in 1970's and summarized by Cavanagh [(1)], revealed what is now a familiar list of complaints. More than 20% of the runners surveyed complained of knee pain, 18% of Achilles tendinitis, 10% of "shin splints" and 7% of "arch injury". An early clinical survey [(2)] found similar results, with knee pain reported by over 25% of patients and Achilles tendinitis, shin splints and plantar fasciitis among the most frequently reported injuries.

Although by 1980 a characteristic profile of running injuries had been identified, the mechanisms underlying these injuries were still unclear. It was believed that repeated impact loading was an important factor. The notion that excessive pronation of the subtalar joint was involved in running injuries was gaining popularity, but no definitive clinical or biomechanical results had been obtained.

The running shoes of the late 1970's reflected some of this uncertainty. The shoes given top ratings by Runner's World Magazine in 1980 had many similarities in design. Typical running shoes featured a cushioned midsole of Ethylene Vinyl Acetate (EVA) foam, woven nylon uppers with suede reinforcements and moulded rubber outsoles. The Editors' selection criteria included price, weight, shock absorption, flexibility and durability. "Stability" and "Motion Control" had yet to emerge as important issues. Some shoes, notably those from the Brooks Shoe Company, incorporated a four-degree varus wedge in the midsole. The concept was controversial at the time and criticised as a form of unprescribed treatment. In retrospect, the concept is now recognized as an early and effective pronation control device.

INJURY SURVEYS AFTER 1980

In the early 1980s, more comprehensive surveys of running injuries confirmed the pattern established by earlier, more *ad hoc* surveys [(3)]. Running accounted for 37% of the more than 10,000 injuries treated at one sports medicine clinic, more than any other recreational activity [(4)]. Importantly, Clement *et al* [(3)] documented the distribution of 1819 running injuries over a two-year period and also identified risk factors associated with injuries of different types. Shoes and surfaces were each implicated as risk factors in about 5% of injuries. “Training errors”, described as behaviours that result in a sudden increase in the loads imposed on the body, were identified as important risk factor. Examples of training errors include a sudden increase in the duration or intensity of training runs, persistent high intensity training, a single severe training bout or race and the sudden return to training after a period of inactivity.Training errors have been implicated in 60-75% of tibial stress fractures [(5)] and 75% of Achilles tendon injuries [(3)].

Reports from this period also confirmed the significance of subtalar joint pronation as a risk factor in running injuries. Of the runners diagnosed with the four most common overuse injuries [(3)] 66% were rated with moderate or severe varus alignment of the lower extremity. Stress fractures have also been linked to varus alignment of the forefoot, rearfoot or tibia [(6)].

It is now generally acknowledged that varus alignment of the lower extremity and training errors are the most prevalent risk factors associated with overuse injuries among runners. Varus alignment and other anatomical factors appear to predispose an athlete to injury, by amplifying the impact-induced internal stresses on bone and soft tissue. Training errors produce increases in the load on the body, to which tissues are unable to adapt, thus triggering injuries.

FUNCTIONAL OVER-PRONATION AND COMMON OVERUSE INJURIES

During normal running, the foot contacts the ground beneath the center of mass of the body, in order to facilitate balance. Consequently, the foot naturally makes initial ground contact in a slightly supinated position (Figure 1a). Supination at contact typically ranges from 0 to 10 degrees relative to the lower leg. Pronation occurs as the foot rotates to make flat contact with the ground, reaching a maximum angle of pronation about midway through the ground contact period (Figure 1b). Although pronation combines eversion and abduction of the foot by rotation about the talo-calcaneal (subtalar) joint and dorsiflexion of the ankle, the dominant component of pronation is calcaneal eversion, which can conveniently be measured using two-dimensional kinematic methods.

The total range of eversion from first contact to mid-stance is typically 10-20 degrees, but may exceed 25 degrees in some subjects. In runners with an inherent varus alignment of the lower extremity, the foot contacts the ground in a more supinated position and must therefore undergo a greater range of motion (functional over-pronation) in order to achieve flat contact with the ground.

Significantly, the talo-calcaneal joint is oriented in a manner that links pronation with internal tibial rotation. This mechanism in the ankle joint has been classically described as an oblique hinge [(7)]. Although more recent studies show the mechanism to be somewhat more complex, the linkage between pronation and tibial rotation is believed to play a role in running injury mechanisms.

The four most common overuse injuries incurred by runners (patello-femoral pain, tibial stress syndrome, Achilles tendinitis and plantar fasciitis) are all associated, to a greater or lesser degree with varus alignment of the lower extremity. In each case, the purported biomechanical link between impact and injury involves functional over-pronation.

In the case of patello-femoral pain syndrome or “Runner’s Knee”, excessive pronation and the associated internal tibial rotation is thought to cause the patella to deviate slightly from its normal alignment relative to the femoral condyles. The resulting increase in contact pressure in the patello-femoral joint leads to painful symptoms. In extreme cases, the high pressures cause degradation of the cartilage and underlying bone (chondromalacia patella).

Excessive pronation has also been implicated in some types of tibial stress syndrome (“shin splints”) [(8)]. In this case, it is believed that functional over-pronation increases the tension in the Achille’s tendon, overloading the insertion of the soleus where breakdown of the surface of the tibia may occur. Similarly, purported mechanisms of Achilles tendinitis include excessive pronation as a risk component. Violent motion of the tendon during impact may lead to micro-tears and tissue degeneration. It has also been suggested that functional over-pronation and internal tibial rotation produce torsional stresses in the tendon, with vascular impairment as a possible consequence [(9)]. Torsional stresses due to excessive pronation are also implicated in the aetiology of plantar fasciitis [(10,11)].

PRONATION CONTROL IN RUNNING SHOES

Since the early 1980's most running shoe manufacturers have included anti-pronation or motion control features in some or all of their products. Such features include stiffer cushioning, stiff heel counters, insole boards, medially - posted midsoles, varus wedges and proprietary cushioning geometries. These devices generally work in one of two ways. Some stiffen the shoe upper and midsole in an effort to physically restrain the motion of the subtalar joint. Other designs modify the geometry of the cushioning in order to reduce the lever arm of the ground reaction force about the subtalar joint, reducing the torque that tends to promote pronation. Firmer, wider midsoles offer a greater lever arm to the ground reaction force, increasing angular displacement and pronation velocity. Softer midsoles increase shock attenuation and reduce angular velocity at the expense of greater rearfoot motion [(12)]. Constructions in which a soft lateral border is combined with a firmer medial post have been found to be effective at controlling pronation [(13)]. The soft lateral border is compressed on contact, attenuating shock and reducing the lever arm of the ground reaction force while the firmer medial border resists excessive pronation. Upper constructions that encourage a close fit between the heel and the shoe can also contribute to motion control [(14)].

The excessive pronation hypothesis is commonly used in shoe design and medical diagnoses. Treatments for running injuries, using orthotics or specifically designed shoes to reduce pronation are often effective in relieving symptoms. Conventionally, athletes with *pes planus* are considered more likely to have hypermobile feet which hyperpronate and require "stable shoes". Conversely, the athlete with *pes cavus* is considered more likely to have hypomobile feet that pronate less and require more cushioned shoes.

Recent research suggests that the detailed mechanisms of injury and treatment through pronation control are not well understood. For example, the movement coupling between eversion of the calcaneus and tibial rotation is not absolute. In one *in vitro* study, only 14 - 66% of calcaneal eversion was transferred [(15)] to tibial rotation. The situation is further complicated by the observation that movement coupling is less for athletes with *pes planus* and greater for those with *pes cavus* [(16)]. Recent studies suggest that variability in coupling may be more important than the degree of coupling *per se* [(17)]. It is also known that the talo-calcaneal joint has variable anatomy, with both two- and three-faceted joints commonly found [(18,19)]. An individual may have a different number of facets on left and right sides.

These findings make it more difficult to make individual footwear prescriptions and confound the running shoe manufacturers' problem of having to meet the needs of a large population of customers with relatively few shoe models. Historically, the manufacturers' strategy was to make shoes with varying degrees of pronation control, offer some guidance on shoe selection and allow consumers to choose. Increasingly, products have cushioning systems with integrated anti-pronation mechanisms that make the stability properties of a shoe more independent of the cushioning properties. These sophisticated shoe designs respond to increasing medial loads by stiffening, the intent being to provide greater resistance to pronation "on demand". Such designs are intended to meet the needs of a wider range of runners with different foot types and pronation mechanics.

Shoe Inserts

Shoe inserts (orthotics) are commonly used in an effort to correct lower extremity alignment problems and to control pronation. Orthotics reduce rearfoot motion by 1-2 degrees, somewhat less than the effect of stability-oriented running shoe. Orthotics have been shown to reduce rearfoot motion, particularly when combined with a stability shoe [(20)] but recent research into their effectiveness is equivocal. Nigg *et al* [(21)] compared the effects of six different orthotic inserts on rearfoot motion during running. None were significantly different from the no-insert condition. Stacoff *et al* [(22)] measured three dimensional calcaneal and tibial rotations using markers placed on intra-cortical pins. Orthotics were found to have only small effects on tibio-calcaneal motions and these were inconsistent among subjects, suggesting that any effects are highly individual. It has been suggested that the proper role of inserts is to reduce muscular work, rather than to align the skeleton or limit motion [(23)].

CUSHIONING IN RUNNING SHOES

The impact between the foot and the ground during a running step has a peak force magnitude in excess of two times the athlete's bodyweight and generates a shock wave that is transmitted through the musculo-skeletal system. The impact shock wave has a typical magnitude of between 5 and 15 times the acceleration due to gravity (5 - 15 g) at the level of the tibia, but is attenuated to between 1 and 3 g at the level of the head. Impact forces and shock magnitudes are influenced by body mass, running speed, touchdown kinematics, shoe properties, surface properties and gradient. Muscle actions in the lower extremity can act to reduce peak impact loads and peak loading rates [(24)].

Repetitive impact loading is believed to be a risk factor in numerous running injuries, including stress fractures, shin splints, cartilage disease and osteoarthritis. Although direct impact injuries (metatarsal and tibial stress fractures, etc.) are reported by fewer than 5% of injured runners [(3)], there are no published injury surveys from the pre-cushioning era, nor studies directly comparing injury rates in shod and barefoot running.

The first "technical" running shoes of the 1970's incorporated a foam rubber midsole between the outsole and the upper to cushioning the impact between the shoe and the ground. Cushioning systems greatly increased comfort, reduced the occurrence of painful feet and allowed many people who would not otherwise have participated to enjoy the "jogging boom".

Cushioning in athletic shoes has been shown to attenuate skeletal shock transients and to reduce peak plantar pressures. Shock absorbing inserts in non-athletic shoes have been shown to relieve heel pain and Achilles tendinitis [(25)] and to reduce the incidence of stress fractures in military recruits [(26)].

A great variety of cushioning materials have been incorporated into the cushioning systems of modern running shoes. These include foamed polymers, viscoelastic materials, air, gases, gels and moulded springs. Materials are generally selected on the basis of their shock attenuation, energy absorption, weight and durability. Although cushioning materials vary considerably, the principles of cushioning are common to all of them. The addition of a layer of compliant material between the foot and the ground distributes impact forces, both temporally (reducing peak forces) and spatially (reducing peak pressures).

Figure 2 compares the results of *in vitro* impact testing of arbitrarily soft and firm cushioning systems. The force-time curve of the two impacts illustrates the basic mechanics of cushioning. The more compliant shoe undergoes greater deformation when impacted, increasing the duration of the impact. The decelerating impulse is thus applied over a longer period of time. This temporal redistribution of the impact force results in lower peak forces and the peak rate of force increase is also lower.

Figure 3 illustrates the manner in which load is distributed spatially by a cushioning system. This figure compares peak pressures on the plantar surface recorded during running at 5 m s^{-1} under different cushioning conditions. Data were collected using an array of pressure-sensors in the insole of the shoe. Typically during running, peak pressures are focused under the heel, metatarsal heads and hallux. With increasing cushioning however, loads are distributed over a greater area of the plantar surface, reducing the magnitude of local peak pressures.

RUNNING SHOES AND RUNNING PERFORMANCE

Distance running performance is primarily determined by physiological factors. Maximum oxygen uptake ($VO_{2\ max}$), fractional use of $VO_{2\ max}$, lactate threshold and muscle fiber type, for example, have all been shown to correlate with successful distance running performance [27,28]. The primary functional role of running shoes is to provide protection from contact with the running surface and there little evidence to suggest that choice of footwear, within normal bounds, has an effect on performance that is great enough to outweigh primary physiological factors.

That noted, footwear has been shown to influence the sub-maximal aerobic demand at a given running speed (“running economy”). Increasing the weight of a shoe, for example, increases oxygen consumption at moderate running speeds by approximately 1% for each 100 grammes of added weight[29]. Cushioning properties also have an effect, with soft-soled shoes reportedly reducing oxygen cost by 1-2% compared with hard-soled shoes[30]. Reducing the flexibility of the forefoot of a shoe reduces energy dissipation at the metatarsal-phalangeal joints [31], but this effect has not been linked to improvements in distance running performance.

Although there has been some popular interest in the concept of “energy return” in feet and footwear[32]), the elastic energy stored and recovered in conventional cushioning systems is thought to be too small to have a direct influence on running economy[33] The mechanism by which cushioning influences running economy is believed to be a kinematic adaptation to the compliance of the shoe sole [234]. Runners are thought to adapt to harder cushioning systems by adapting their running style in a manner that compensates for the reduced shock attenuation; by increasing knee flexion velocity for example [35]. These adaptations require muscle action and incur an energy penalty; the “cost of cushioning”. Conversely, greater shock attenuation in the sole reduces the metabolic cost of cushioning with consequent small reductions in the oxygen consumption.

SHOE SELECTION

The great anatomical, physiological and kinematic variation among runners makes it very difficult to make general prescriptions for the selection of appropriate running shoes. In general, athletes should select shoes that fit well, are comfortable and with cushioning that feels neither too hard nor too soft. Subjective assessments of fit, comfort and shock attenuation are generally reliable guides to the actual mechanical properties of the shoes. Stability properties of shoes cannot be perceived reliably, however. Runners who need pronation control must therefore rely on identifying features, such as firm cushioning, medial posting and heel fit, that are known to influence pronation.

It is common practice to select different shoes for competition than for training. In the case of marathon events, this may be inadvisable for several reasons. Firstly, while racing shoes are lighter than training shoes (by as much as 100 grammes per shoe), they are also less protective. The added weight in a training shoe is largely due to additional cushioning and support features. Secondly, during training, the runner’s body acclimatises to the mechanical load levels experienced. Suddenly changing the load regime by switching to a lighter, less cushioned shoe could constitute a “training error”, increasing the likelihood of injury if other risk factors are present. Finally, while the weight savings may reduce oxygen cost of running by 1%, the savings is partly or wholly compensated for by the increased cost of cushioning and the net performance benefit may be minimal. It is up to the individual runner to balance the value of this small potential advantage with the increased risk of injury. That balance, in turn, will depend on whether the subject is an elite athlete with a possibility of winning the race or a recreational runner hoping to complete his or first marathon.

CONCLUSION

Since the first London Marathon, our knowledge of running injury mechanisms has been considerably enhanced. From an initial focus on impact as a primary cause of overuse injuries, attention has shifted to the role of secondary effects and internal stresses caused by instability and excessive motion of the joints of the lower extremity. We have also learned in that time that injury risk is increased by hyperpronation, muscular insufficiency, injury history and training habits. Current research suggests that injury mechanisms are variable and highly individual.

The sports shoe business is driven by the need to produce new products that are competitive, profitable and fashionable. Despite these demands, major athletic shoe manufacturers have generally responded to new knowledge about running injuries and injury mechanisms by introducing new designs and components intended to make their products more functional. The first cushioning systems were developed in response to concerns about the effect of repeated impacts between the foot and the ground. As the pronation hypothesis linking peripatellar knee pain and other injuries to excessive rearfoot motion gained popularity, shoe designs intended to reduce pronation were developed. Currently, as our awareness of the individuality and specificity of injury mechanisms increases, shoe manufacturers are responding by developing models that allow more customisation to meet individual needs.

Despite these advances, it is not known to what extent running shoes reduce the risk of running injury. This is largely because definitive experiments would require, unacceptably, increasing the injury risk of some subjects. Indirect evidence can be found in the laboratory, where shoes have been shown to affect the hypothetical causes of injury (e.g. by reducing impact shock, plantar pressure and rearfoot motion). Such evidence is only as good as the purported injury aetiology however, and more research is necessary in this area.

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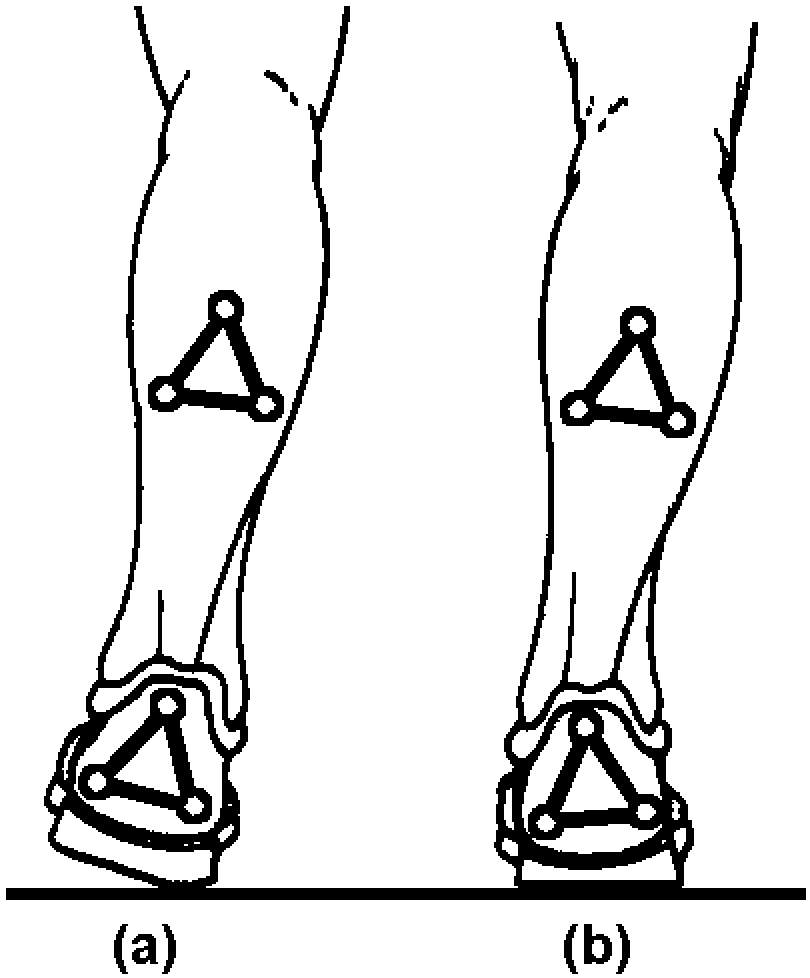

Figure 1: Rear view of the orientation of the right foot and lower leg during ground contact in running showing (a) supination of the talo-calcaneal joint at initial heel contact and (b) pronated talo-calcaneal joint at mid-stance.

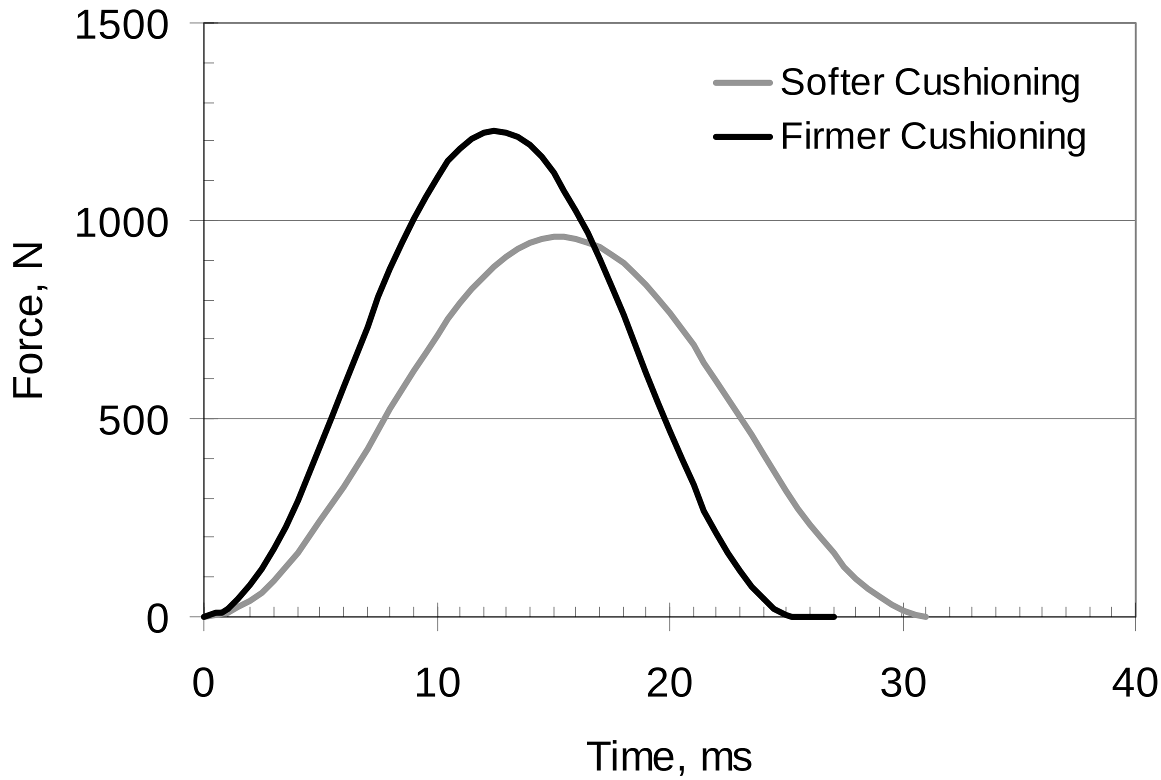

Figure 2: Effect of cushioning on force-time during impact.

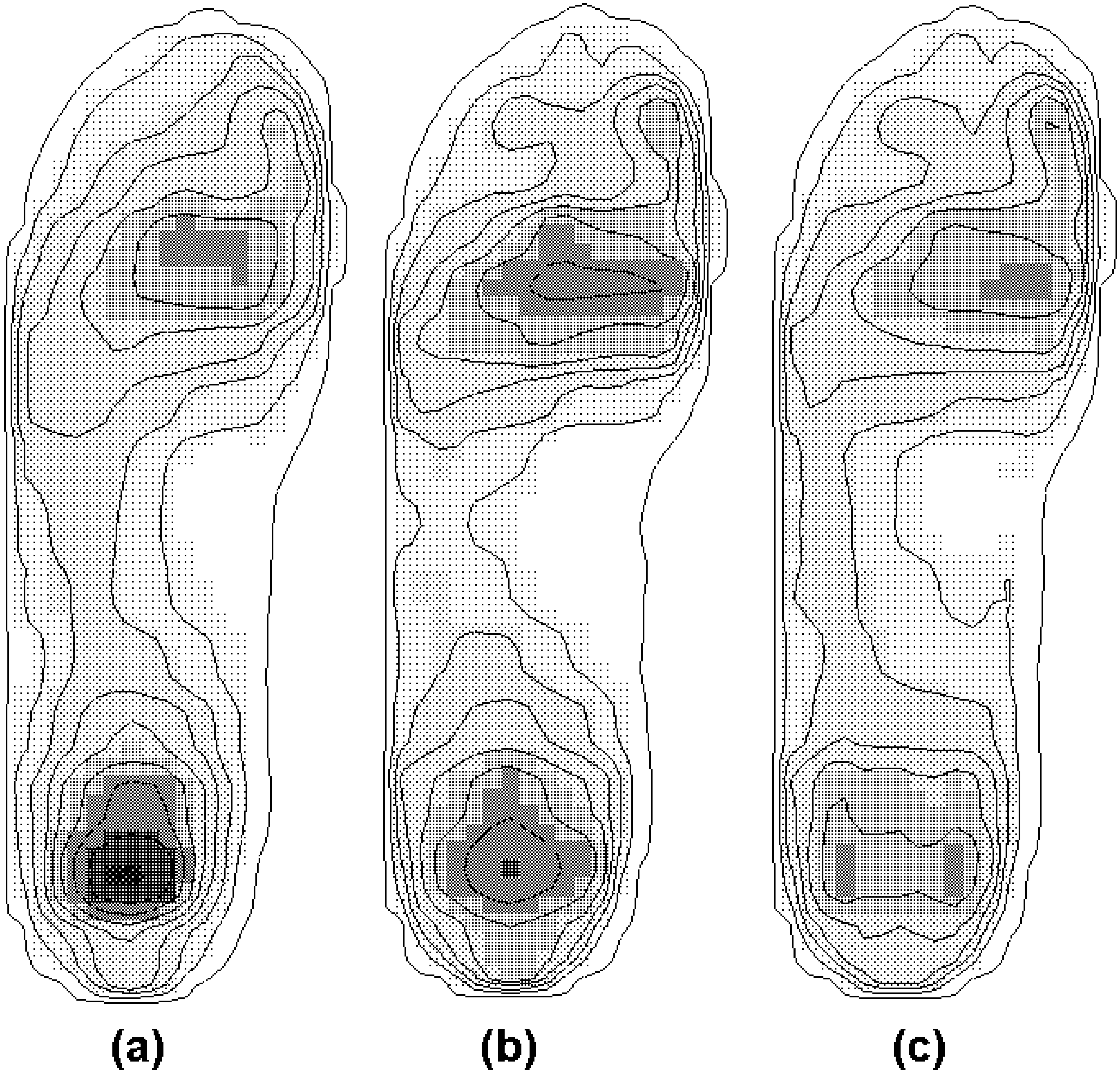

Figure 3: Peak plantar pressure distribution during running at 5 m s^{-1} under different cushioning conditions: (a) minimally cushioned shoe (b) moderately cushioned shoe (c) well-cushioned shoe. Each map is the grand mean of 60 running steps (5 steps from each of 12 subjects) and the pressure contour interval is 50 kPa.