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Running-related injury prevention through barefoot adaptations

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ABSTRACT

ROBBINS, S. E. and A. M. HANNA. Running-related injury prevention through barefoot adaptation. *Med. Sci. Sports Exerc.*, Vol. 19, No. 2, pp. 148–156, 1987. A number of reports indicate an extremely low running-related injury frequency in barefoot populations in contrast to reports about shod populations. It is hypothesized that the adaptations which produce shock absorption, an inherent consequence of barefoot activity and a mechanism responsible for the low injury frequency in unshod populations, are related to deflection of the medial longitudinal arch of the foot on loading. It is also hypothesized that the known inability of this arch of the shod foot to deflect without failure (foot rigidity) is responsible for the high injury frequency in shod populations. To evaluate these hypotheses, 17 recreational runners were analyzed to study the adaptive pattern of the medial longitudinal arch of the foot due to increased barefoot weight-bearing activity. Changes occurred in the medial longitudinal arch which allowed deflection of this arch on loading which substantiated the hypotheses. Other evidence suggests that sensory feedback largely from the glabrous epithelium of the foot is the element of barefoot activity which induced these adaptations. The sensory insulation inherent in the modern running shoe appears responsible for the high injury frequency associated with running. The injuries are considered "pseudo-neuropathic" in nature.

RUNNING, INJURY PREVENTION, PROTECTIVE FOOTWEAR, BIOMECHANICS

A large and vexing problem that is continually encountered by sports medicine practitioners is the high frequency of running-related injuries (6, 9, 10, 18). Such injuries are commonly known as "overuse injuries," probably because when this term was first used, the injuries were observed mainly in competitive distance runners as they increased their training mileage. With the present popularity of running as a mass participation recreational activity, injuries are seen very frequently in people running very modest mileages and reasonable amounts of time (9, 10). Based on these observations, the authors prefer using the term "running-related injuries" for this group of sports injuries rather than overuse injuries.

The types of injuries considered to be running related, mainly involve injury to bone and connective tissue in the lower extremities. There has been some variability in classification systems, but there can be little doubt sports medicine practitioners face a similar array and frequency of running-related injuries (6, 10) (Fig. 1).

There is among sports medicine practitioners, coaches, and exercise physiologists a rather uniform impression as to the ultimate cause of running-related injuries. The sudden loading of the lower extremities on contact with the weight-bearing surface produces an extremely sharp rise of vertically transmitted force (impact). It is this impact that is considered to be the most basic element which causes running-related injuries (3, 4, 13, 18, 24, 25). This force has been shown to be equal to about 2.5 times one's body weight if applied statically. Other physiologically similar sports such as bicycling and cross country skiing subject the lower extremities to similar net loads, but the rate of loading is lower. Lower extremity injury is so uncommon in such sports that it has never been identified as a significant problem.

Despite the modern engineered running shoe, a sports medicine clinic reported a large series of running-related injury referrals with an average weekly mileage at the time of injury of 19 miles for women and 27 miles for men (9). Practitioners of sports medicine have observed injuries in runners using every shoe model available. The above reports can hardly be considered an endorsement of the modern running shoe as a protective device. These data have lead the authors to suspect that the basic assumptions used in running shoe design are incorrect.

This high injury frequency in sports involving running and jumping has lead many to conclude that the lower extremities and particularly the foot to be of a poor design, an unusually fragile structure unable to sustain the use associated with running without injury, thus requiring additional protective devices (22).

The foot of the normally shod individual is described as rigid, i.e., the main bony arches are unable to yield on normal loading. Relatively unyielding connective tissue appears to sustain the foot arches (1). The intrinsic foot musculature, which could give the foot a yielding quality, is described as atrophic, almost vestigial with adhesions to other internal foot structures (22). This description conveys the impression that the foot of normally shod individuals is beyond rehabilitation of internal foot musculature which could allow deflection on loading and thus absorb impact.

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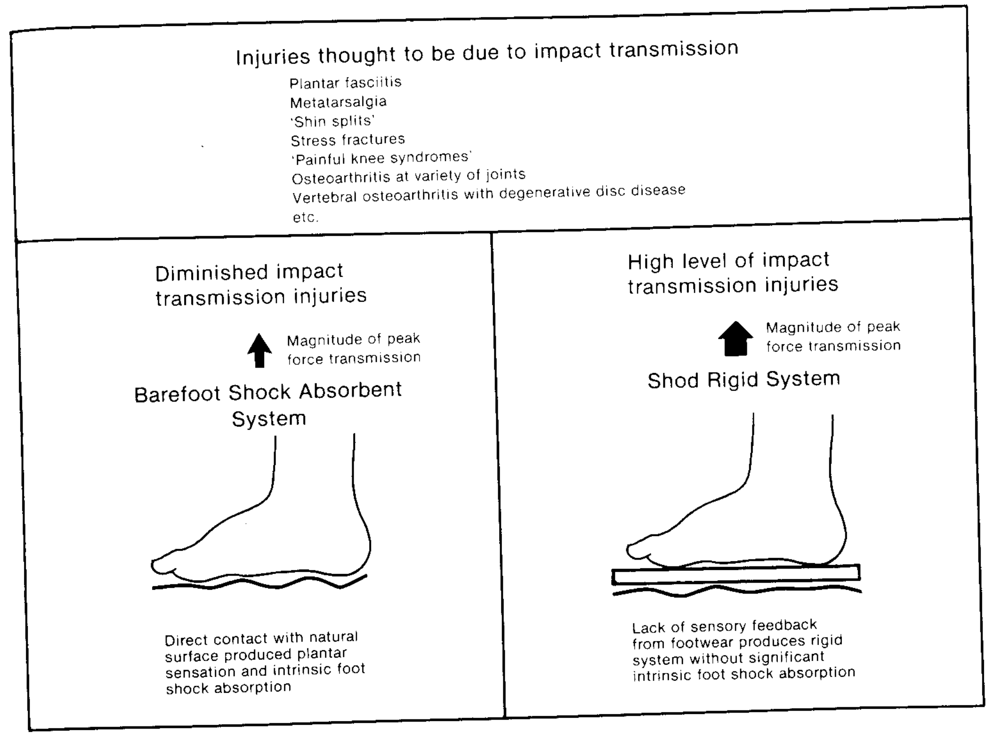

Figure 1—Graphic presentation of the hypotheses formulated by the authors.

The protective footwear used in running is designed based on the above assumptions. The foot is treated as a delicate and rigid object which is placed in a high impact environment. It is thus "packaged" with shock-absorbing material. It is this "packaging" solution which the authors suspected could be incorrect and a possible cause of the high injury frequency reported.

The opinion that the lower extremities are inherently fragile goes against the authors' understanding of the concept of natural selection. In addition, the authors have assembled a vast body of data in the form of published and personal reports from educated observers as to running-related type of injury frequency in barefoot populations. All of the reports and observations consistently point to a very low frequency of this type of injury in such populations. The authors have not received a single communication which indicates a high injury frequency in barefoot populations. This is completely in opposition to impressions and data from shod populations. The following are examples:

1) Reports about barefoot runners in international competitions do not mention frequent injury. Their records in competitions attest to their extreme durability.
2) Observers of barefoot populations mainly in underdeveloped countries indicate the rarity of lower extremity injury in such populations.
3) A West German trained physical education instructor has trained literally hundreds of barefoot people in sports involving running and jumping over a period of many years. He is unable to recall a single impact-related type lower extremity injury in this population.
4) Reports from countries where both barefoot and shod population co-exist, as in Haiti, indicate high rates of lower extremity injury only in the shod population. Barefoot weight-bearing is considered by many Haitians to induce resistance to lower extremity injury.
5) In countries where people have spent part or all of the year barefoot, as in the West Indies or certain countries in Europe and Asia, there is little evidence of nor reports of frequent impact-related lower extremity injuries.

A paradox is presented of lower extremity fragility associated with the wearing of protective footwear and relative resistance to injury in the barefoot or unprotected state. To explain this paradox, the authors hypothesized that there exist adaptations associated with barefoot activity that provide impact absorption and protection against running-related injuries. An adaptation involving foot arch deflection on loading is hypothesized to be an important adaptation providing impact absorption. In contrast, it is hypothesized that the known rigidity of the shod foot may explain the reported high injury frequency in North American runners (Fig. 1).

Finally, it is hypothesized that the traditionally shod foot of the North American is capable of rehabilitation of the internal foot structures (intrinsic musculature), a subject which has been ignored by investigators. The investigation which is reported here examines changes in force-deflection characteristics of the main longitudinal arch (medial) of the foot associated with increased barefoot weight-bearing activity among typical North American recreational runners.

MATERIALS AND METHODS

Equipment development. Traditional force platforms give net readings at the skin-platform interface. No information is obtained as to how any substructure such as the arched systems of the foot contribute to this net result, an assessment of its contribution to the modification of vertical force transmission. A platform was developed that could obtain reliable measurements of force-deflection characteristics of the arched subsystems internal to the foot. With this device, a reference point is used which is approximately equidistant to the ends of the longitudinal and the transverse arches of the foot. A ball and socket type joint is placed under the platform at this point so that when the platform is balanced, there is repeatable loading on either side of the arch to be examined. Normal load is controlled by means of a spring balance. Foot positioning on the platform is aided by the use of easily ascertained bony landmarks on the perimeter of the foot, and with the aid of a matrix which is permanently fixed to the top surface of the platform (Figs. 2 and 3).

The platform was constructed of rigid wood and plastic. Two bubble type levels were inserted perpendicular to each other and parallel to the main axes (Fig. 3). The central reference point was positioned over a ball and socket type joint (Fig. 3). The subject is required both to balance with respect to the levels and to obtain standardized load prior to obtaining the X-ray. The platform was used to obtain radiographs in the lateral position on weight-bearing (Figs. 4 and 5).

X-ray techniques. Lateral radiographs were obtained during relaxed barefoot weight-bearing. The cassette was located parallel to the long axis of the platform in a vertical position to obtain horizontal beam lateral view radiographs (Figs. 4 and 5). The X-ray machine used was a Picker single-phase type. The cassettes used were Dupont Rare Earth Extremity Extreme Detail. The machine settings were approximately 100 mA and 50 kV with a 1/320 s exposure time.

System repeatability. The repeatability of the system was determined by overall foot weight-bearing imprint length measurements. Serial X-rays in the number required to determine repeatability was considered to be of limited advantage over the imprints and

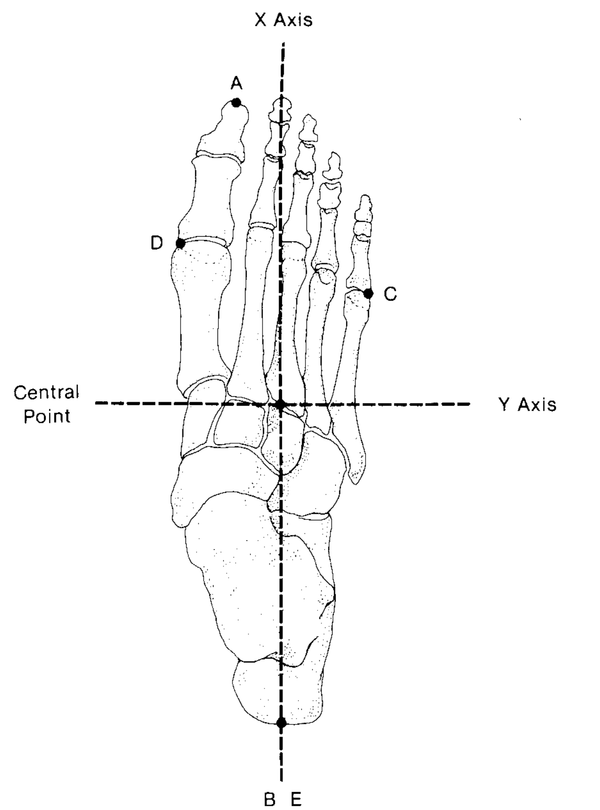

Figure 2—The X and Y locating points; easily ascertained bony landmarks that were used to position the foot with the aid of the surface matrix.

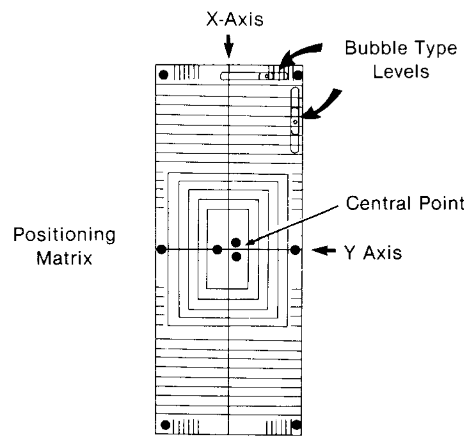

Figure 3—Weight-bearing platform (view of top surface).

of possible risk to the subjects. The high degree of repeatability of the technique is evidenced by serial recordings. The standard deviation was under 0.5 mm, which was the limitation of the measuring instrument. A change of greater than 1 mm should be considered significant.

Subjects. The subjects consisted of 17 volunteer recreational runners. There were 14 men and 3 women. The controls were a sub-group of the volunteers who entered the study as the others, but were unable to increase their barefoot weight-bearing activity for reasons of inconvenience or time constraints. The subjects were asked not to significantly alter their running mileage. The subjects were all informed by standards of the Declaration of Helsinki of the World Medical Association.

Pre-experimental period. The subjects recorded a detailed running history with emphasis on footwear, injuries, and barefoot weight-bearing activity prior to the experiment. The subjects were all instructed about the maintenance of a "training log," which recorded the duration and type of barefoot weight-bearing activity during each day of the experiment.

The subjects were told to increase barefoot weight-bearing activity as much as possible both at home as well as outdoors. Barefoot running and walking were encouraged. The investigators recommended that this activity be increased gradually over a period of several weeks. The duration of the experiment was explained to be approximately 4 months. Foot data were collected prior to the experiment, consisting of foot imprints taken during relaxed barefoot weight-bearing with applied normal loads of 15 and 55 kg for men and 15 and 45 kg for women, and X-rays which were taken at the heavier load only.

Experimental period. At monthly intervals, six imprints and two X-rays were taken of the subject's right foot during relaxed barefoot weight-bearing. Three imprints were taken at each of the two loadings. One good quality anterior-posterior and one lateral X-ray were taken only at the heavier load.

Data analysis. The lateral X-rays taken during relaxed barefoot weight-bearing were analyzed by a radiologist. The distance was measured from the medial tubercle of the calcaneus to the most distal point of the first metatarsal head (Fig. 6). All experimental subjects were required to perform greater than 1 h of increased barefoot activity daily.

RESULTS

Medial longitudinal arch span. A positive change is indicated by significant (1 mm) shortening of the medial longitudinal arch with increased barefoot weight-bearing activity, or lengthening with cessation of increased barefoot weight-bearing activity (Figs. 7 to 10). Of 18 readings from the experimental group, 13 changed positively, two changed negatively, and three did not change ($P < 0.05$). Of the controls, one changed positively and 10 changed negatively ($P < 0.05$). The trend toward decreased span was present without respect to the height of the arch prior to the experiment,

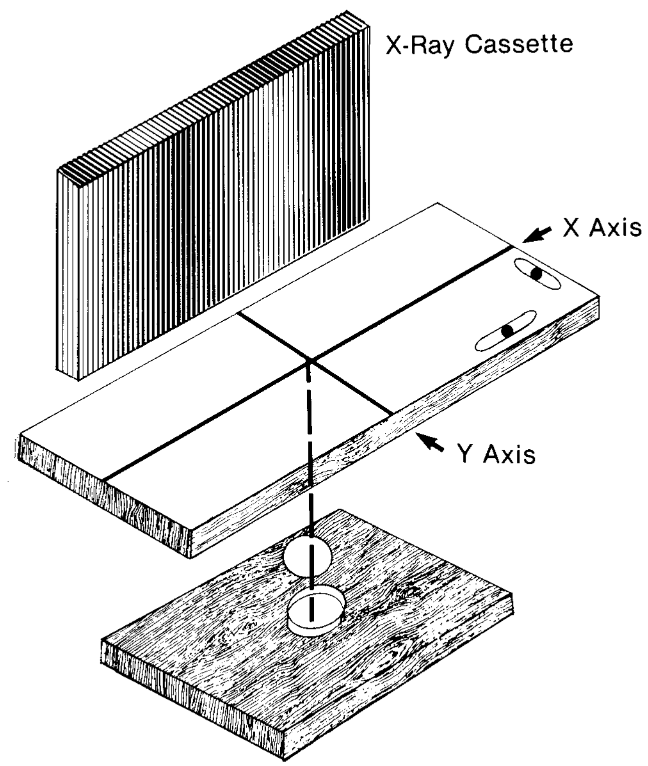

Figure 4—Location of equipment for lateral view.

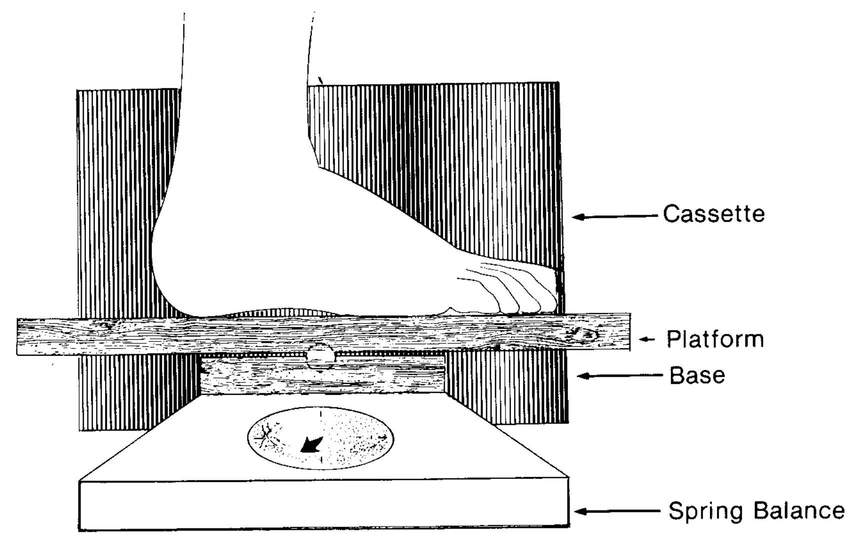

Figure 5—Obtaining lateral view.

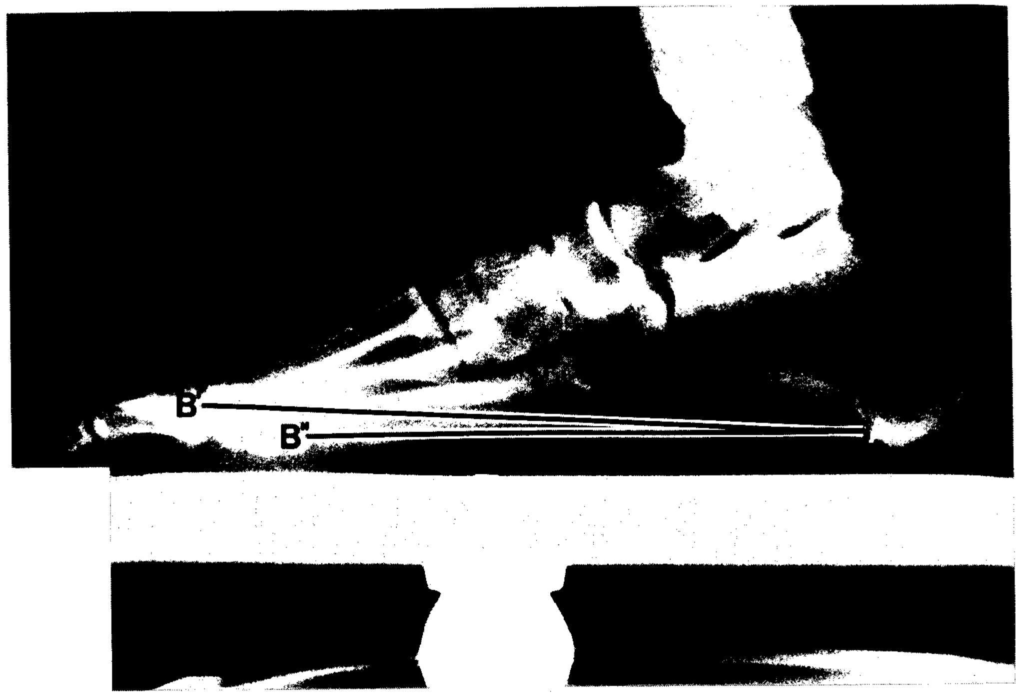

Figure 6—Longitudinal arch span measurements.

LEGEND
A Medial Tubercle of the Calcanus
B' 1st Metatarsal (anterior)
B" 5th Metatarsal (anterior)
B-A Medial longitudinal arch span.
B-A Lateral longitudinal arch span.

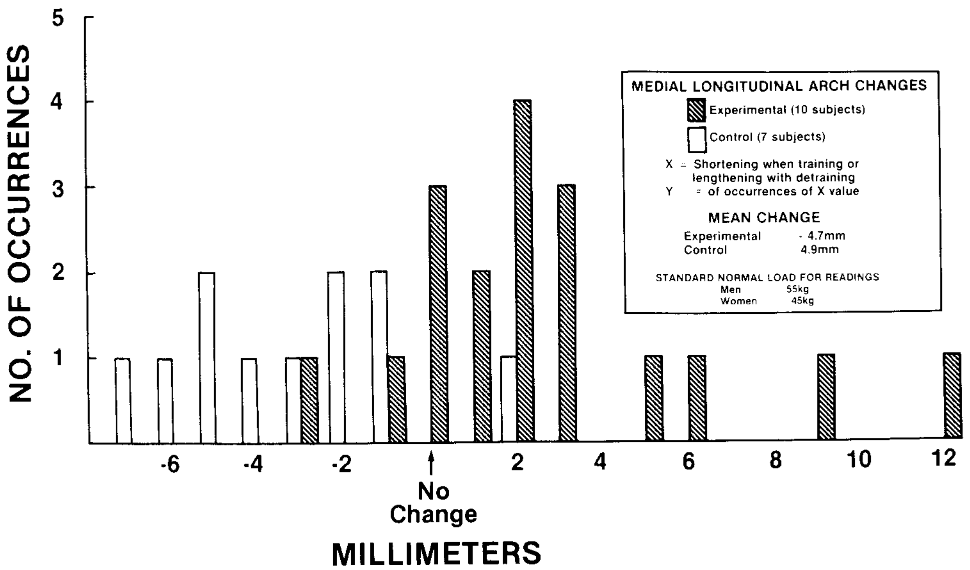

Figure 7—Medial longitudinal arch changes.

nor the subject's age, sex, running mileage, or footwear. The mean change for the experimental subjects was +4.7 mm. The mean change for the controls was −4.9 mm.

DISCUSSION

Electromyographic studies have repeatedly confirmed that there is no tonic activity of the intrinsic muscles of the foot during relaxed weight-bearing in normally shod volunteers (1). The experimental changes of shortening of the medial arch and load redistribution to the digits can only be explained by an activation of this normally inactive musculature associated with increased barefoot weight-bearing activity. The progressive change over 2 and 3 months is also consistent with skeletal muscular conditioning. The data clearly demonstrate that the normally shod foot is capable of rehabilitation of foot musculature.

While the demonstrated adaptation has been shown

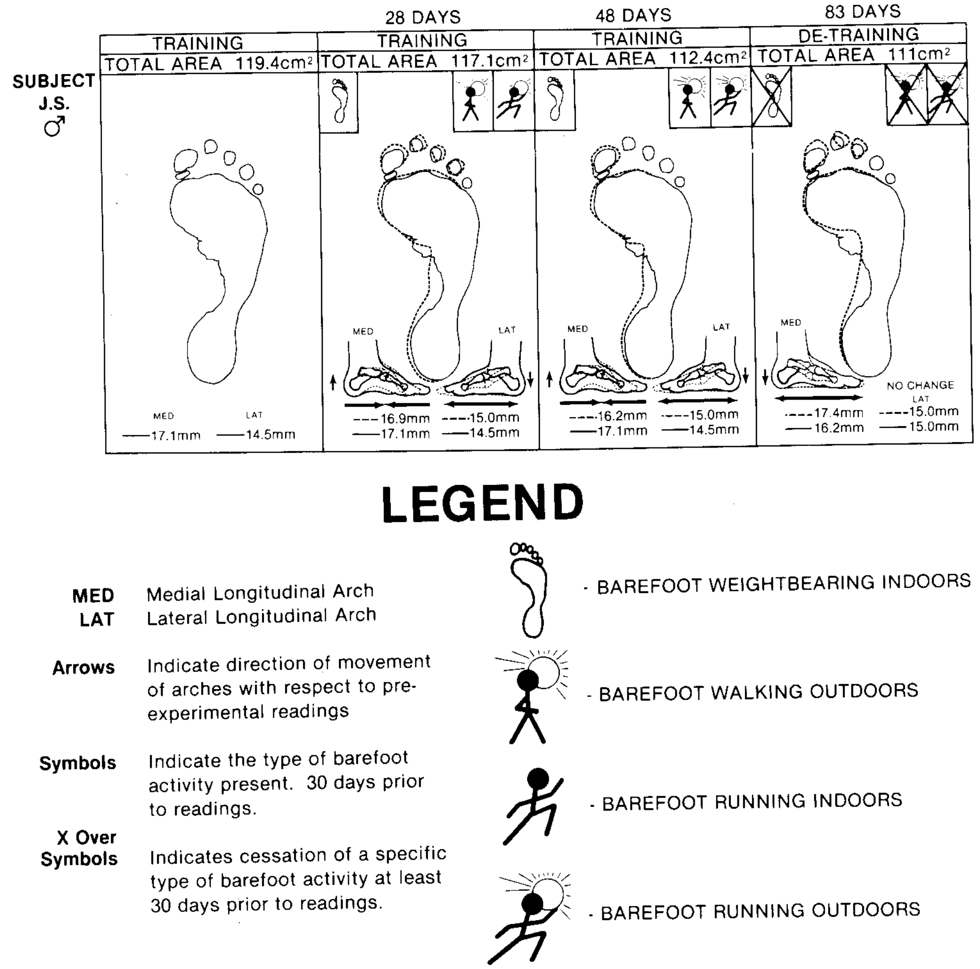

Figure 8—Sample comparison; male experimental subject.

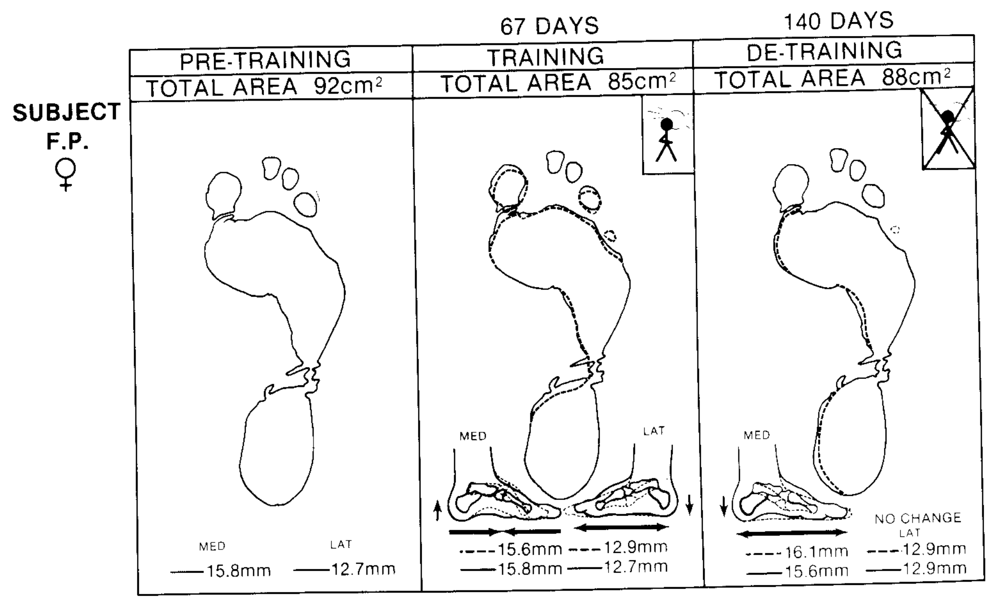

Figure 9—Sample comparison; female experimental subject. See Figure 8.

to exist in the laboratory setting while standing on a platform, the question remains whether this adaptation is actually used *in vivo* when running, walking, standing, and jumping.

Technically, it would be very difficult to obtain X-rays of the arches of the foot when running, in order to display this adaptation. However, the following information strongly supports the use of this adaptation *in vivo*.

Reports confirm that, in traditionally barefoot populations, the foot appears highly arched when unloaded and flattens considerably when loaded (22, 26). This

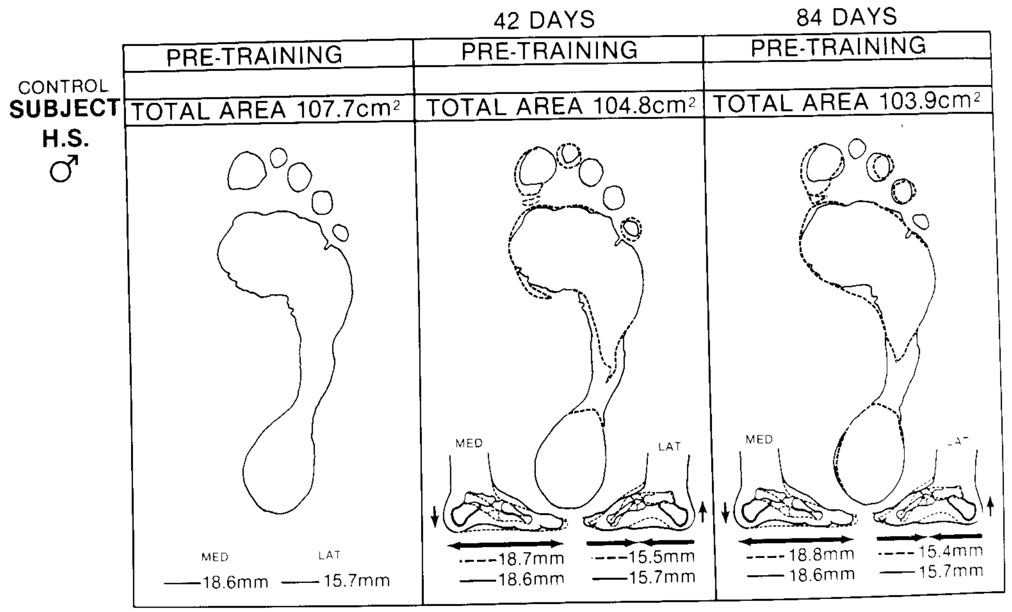

Figure 10—Sample comparison; male control subject. See Figure 8.

phenomenon has not been reported in shod populations. Similar observations have been made while observing bipedal terrestrial primates. This information is relevant, as primates not only share a similar foot structure with man, but they are also the only species other than man to possess Meissner corpuscles, a neuroreceptor of the glabrous skin (21).

Medial arch rising and shortening due to activation of intrinsic musculature allows the foot to act as a dynamic impact dampening structure rather than merely as a lever for propulsion as described by many authors (4, 13, 18). The load on impact is transmitted vertically over the time of the deflection of the medial arch. This adaptation appears capable of preventing injuries above the arch thought to be due to vertical force transmission, such as the most common running-related injuries (Fig. 1).

The medial arch shortening due to increased intrinsic foot muscle tone also provides an extremely attractive hypothesis as to the cause and ultimate prevention of a poorly understood and poorly treated condition commonly found in sports involving running and jumping: plantar fasciitis. This condition involves inflammation of the plantar fascia at its attachment to the calcaneus. The electromyographic evidence previously given implies that unyielding connective tissue, as the plantar fascia, normally acts as the support of the medial longitudinal arch in North American populations. It is possible that foot impact produces tremendous strain at the fascial attachment and induces plantar fasciitis. Barefoot activity induces an adaptation that appears capable of transferring this impact to the yielding musculature, thus sparing the fascia. Support for this hypothesis could come from studying the incidence of this condition in traditionally barefoot populations. The reports that the authors have received indicate a low frequency of plantar fasciitis in barefoot populations.

The limited number of 17 subjects in the present experiment are insufficient for a detailed analysis of the sub-categories of barefoot activity that best induced the adaptations. However, there were certain factors present in the subjects with the greatest adaptations. They are as follows:

1) high total barefoot weight-bearing activity
2) walking outdoors with bare feet
3) running outdoors with bare feet.

The irregular character of the contact surface seemed to be the element that was present in the subjects with the greatest adaptation. This is consistent with the hypothesis that plantar sensory feedback may induce intrinsic foot shock absorption.

It should be noted that the intrinsic foot musculature that raised the medial longitudinal arch originates at the medial tubercle of the calcaneus, traverses the metatarsal-phalangeal joints, and inserts at the middle phalanx of the digits. When this musculature contracts, the arch rises, the digits plantar flex, and the contact at the medial-posterior joints is diminished. If the metatarsal-phalangeal joint location has a low pain threshold compared to other locations on the plantar surface, the barefoot runner could unknowingly be activating his intrinsic foot shock absorption system in his attempt to make barefoot running comfortable, by avoiding the more sensitive location. One can easily appreciate the frequency of foot contact with rigid small objects in the natural barefoot state.

The authors have recently completed an investigation of 100 volunteer subjects which determined the pain threshold from acute skin deflection at different regions on the plantar surface. The area of the first metatarsal-phalangeal joint was found to have a significantly lower pain threshold than the heel pad or the distal digits (unpublished data).

To appreciate the importance of somatosensory feedback in the prevention of injury, the following neuro-

physiology and medical concepts are required. The plantar epithelium shares only with the palmar epithelium, an extremely high density of neuroreceptors which respond to small discrete displacements, directionally applied force (shearing force), and low intensity repetitive force (vibration) (17, 27). These mechanoreceptors have a relatively low threshold (5, 12, 14, 15). There is another group of receptors which respond to similar forces, but such high thresholds that they only respond to mechanical stimuli intense enought to induce tissue damage (nociceptors) (2, 5, 7, 11, 16, 19). These two groups of receptors are responsible for the perception of pressure and pain.

The data suggest that, in our subjects, their normal footwear prior to the experiment did not produce the sensation necessary to induce protective adaptations inherent with barefoot weight-bearing activity. It is obvious that footwear with soft flexible polymer foam and a relatively inflexible rubber sole does not allow discrete skin deflections from irregular surfaces. Foam, in addition, has vibration-dampening properties. It has been elegantly demonstrated that there is diminished shearing force in the barefoot state (20). The shearing force which is applied by the plantar skin when barefoot is transferred to the shoe lacings and counter of the shoes when shod.

It appears likely that the perception of pain and pressure from the very sensitive plantar skin on impact is diminished in modern running footwear; thus, the runner is not induced by sensation to diminish impact through using the demonstrated medial arch adaptation nor to use other mechanisms, such as the alteration of his or her running mechanics to diminish impact. This could be as simple as minimizing the height of his or her running action. The shod runner is completely dependent on the footwear for protection. This dependency on footwear for protection in a low impact environment of walking or standing may be of little consequence. In the high impact environment of running and jumping, the lack of protective adaptations would again be of little consequence if the footwear effectively diminished the rapidly applied vertical force in related injuries. Unfortunately, it has been recently shown that, *in vivo*, impact remains unchanged whether the runner uses soft running shoes, hard running shoes, or bare feet (without a barefoot adaptation period) (8).

The modern running shoe and footwear in general have successfully diminished sensory feedback without diminishing the injury inducing impact, a dangerous situation. The mode of injury follows the medical model of a neuropathic injury. The authors have introduced the term "pseudo-neuropathic" for injuries caused by mechanisms similar to the above medical model, but without prior neurological damage. Instead, a man-made device masks sensation and thus does not allow protective behavior.

Neuropathic injuries are caused by impaired somatosensory feedback. While such injuries are reasonably common, perhaps the most classic examples are the "Charcot joints," described by the eminent classical pathologist and faith healer, Charcot. This condition of almost complete joint obliteration has been shown to be caused by the lack of somatosensory feedback from injury-provoking events due to the neurological damage of tertiary syphilis (23).

The runner, like the neuropathic syphilitic, damages his or her lower extremities due to lack of somatosensory feedback-mediated protective behavior. Ultimately, this is due to insufficient somatosensory feedback due to the running shoe, which gives the runner the illusion that he is well protected. The first sign of overload to the system may be damage to the relatively poorly innervated (compared to the plantar epithelium) bone, ligament, cartilage, or fascia.

In addition to the sensory insulation of footwear, there are several major design features present in nearly all running shoes which could interfere with the demonstrated adaptation. The arch support, which is present in all running footwear, would interfere with the downward deflection of the medial arch on loading. Furthermore, the use of orthotics, or other structures that are fitted to the mould of the soft tissues of the foot, could cause similar difficulty. Such designs occur when an engineer looks at the foot as an inflexible lever which is delicate and thus requires packaging. Various myths persist about foot behavior due to poor understanding of its biology.

The solution to the problem of running-related injuries could be as simple as promoting barefoot activity, but this is not a practical solution for most. There are social restraints. In addition, the bare foot may poorly adapt to man-made surfaces and temperature extremes present in most developed countries. The ultimate solution may well be shoe modifications, which induce intrinsic foot shock absorption and avoidance behavior. Such devices are being developed and tested on runners.

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posium: age as a rmance—chronologic

its, is a contributing factor. One of the consequences of this "graying of America" is expected to be a change in current retirement practices. During the past several decades, there has been a steady decline in participation by older people in the work force because of a trend toward early retirement. Recently, there has been a concertive effort directed at reversing this trend. This includes a challenge to the use of age criteria in personnel policies for both retirement and hiring. Congress, in its wisdom, has passed legislation (Age Discrimination in Employment Act or ADEA) which protects people age 40 to 70 from discrimination in hiring and forced termination from employment based solely on age unless age is a Bona Fide Occupational Qualification (BFOQ). The total elimination of mandatory retirement based solely on age is under consideration. (Legislation was passed since this presentation.) "Work life extension" is the term used to describe the desire of many older persons to continue participation in the labor force because of job satisfaction, financial, and other reasons. In these proceedings, we learn more about the demographics and epidemiology of aging and these trends toward work life extension, particularly by Professor Poulsen.

Dr. Shephard has reviewed the physiologic and pathologic changes that occur with aging and ways in which we might slow our "biological clocks." Differences or variability in the rate of aging and in functional capacity at any age primarily result from differences in life habits. Because there is great variability in rate of aging, there is often considerable differences between chronological and functional or physiologic age. Dr. Sharkey informs us about approaches for testing for physiologic age. The relevance of these latter two topics to age discrimination in employment and the BFOQ issue become obvious. As alluded to earlier, one of the concerns about employing workers in the protected age range, particularly in protective occupations, is concern for public safety. This is primarily based on sterotyping older people as frail and incompetent and not being able to "cut the mustard." Dr. Davis indicates how to evaluate job competencies, particularly in protective occupations and the military. Such testing allows a valid means of screening out those at any age who are incapable of adequately meeting valid job-related physical requirements and is not discriminatory according to the courts.

Since cardiovascular disease is the prime killer in the United States and the incidence increases with age, there is also concern that older people in strenuous or hazardous occupations will place themselves or the public in jeopardy due to the risk of sudden death or heart attacks on the job. My discussion suggests how we can identify by simple tests vulnerable people at any age who are at high risk for coronary heart disease as well as cerebrovascular accidents or strokes. Although aging increases risk of coronary heart disease, there are other important risk factors in the pathogenesis of cardiovascular disease. These include blood cholesterol and blood pressure levels, cigarette smoking, diet and exercise habits, and other factors that can be readily

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