Structural relationship between foot arch length and height and the relavtive effects on foot strength (stability) and impact loading (shock absorption) while barefoot, shod, shod with custom orthotics, and shod with a proprioceptive insole device ("the Barefoot Science Foot Strengthening System").

Rob Burke B.Sc. KIN and Reggie Reyes B.Sc. KIN

August 2002

Abstract

Recent research [1, 2, 3] has demonstrated a clear indication that there is a direct correlation between the degree of hallux dorsiflexion relative to activity levels and improved structural alignment in the lower limbs—quite likely a defensive response to better prepare the body to reduce potentially harmful stresses. The research reinforced the hypothesis that this muscle activation is a natural adaptive response to activity levels during barefoot gait and it is virtually eliminated during regular footwear use. This adaptive proprioceptive muscle activation—necessary to optimally align and stabilize the foot prior to and during weight bearing ground contact, as seen during barefoot gait—was demonstrated during the use of a proprioceptive insole device in footwear. In addition, in the shod only condition, this adaptive proprioceptive muscle activation was virtually absent during all activities as demonstrated by negligible dorsiflexion through all phases of gait and dramatically compromised lower limb alignment.

Outside of acute trauma, it is commonly accepted that most foot-related pathologies arise from unhealthy stresses generated by a biomechanically unsound structure that has been subjected to excessive repetitive activity. Acute or chronic symptoms manifest as a result of varying levels of intensity.

Custom orthotics and similar products are often recommended by medical professionals in an attempt to stabilize the subtalar joint (by supporting the arch) and "correct" the poor biomechanics of the foot. [4, 5, 6, 7, 8, 9, 10] Contrary to claims of correcting biomechanical alignment that are commonly made by those who support orthotic use, research has shown that the relative change in structural alignment is minimal. [6, 11] More accurately, the orthotic simply introduces a new ground interface angle to the plantar surface of the foot.

It is hypothesized that the improved structural integrity of the foot's arch system while using the proprioceptive insole device in footwear is superior to the improved structural alignment benefits derived from custom orthotics. The purpose of this study is to attempt to quantify the varying degrees of structural integrity (strength/stability) of the foot's arch system and the corresponding horizontal forces in the plantar region while barefoot, shod, shod with custom orthotics, and shod while stimulated by a proprioceptive insole device.

The application of simple physics can provide insight into the structural integrity of the foot during gait. Although the functional and physical characteristics of the foot change during the phases of gait, it is every effective to freeze the dynamics of the gait cycle at given points in time to analyze the structural characteristics of the foot.

In an effort to gain better understanding of the functional stability of the foot during gait, cinematographic techniques were used to freeze the positioning of the foot in the gait cycle. Key measurements were taken from twelve subjects on their foot's anatomical landmarks that are analogous to the apex and distal ends of the foot's arch structure. In addition, weight bearing x-ray protocols were developed to analyze the actual relative structural changes in bone alignment. The relationship between the anatomical landmarks on the subjects' feet during passive and active dorsiflexion of the hallux was also recorded and the associated changes in plantar fascia tension and apex arch height were also determined.

Trigonometric relationships were calculated to estimate the relative structural changes in the foot incorporating hallux dorsiflexion, arch height (strength/stability), and tension on the plantar fascia.

As expected, it was found that apex height of the arch system and the associated structural integrity of the foot's arch system was positively correlated with the dorsiflexion of the hallux. The greater the dorsiflexion, the higher and more stable the arch system appeared to be. It was also confirmed that tension on the planter fascia was reduced as the apex of the arch system increases.

For all subjects, the barefoot condition demonstrated the greatest structural integrity in the arch system; the highest degree of hallux dorsiflexion, the highest arch apex (greatest structural strength/stability), and the lowest tension on the plantar fascia, when compared to the shod conditions. For all subjects, the shod, as stimulated by a proprioceptive insole device condition, demonstrated structural integrity in the arch system close to that of the barefoot condition; and far greater structural strength/stability (up to 6.7 times greater) and far lower tension on the plantar fascia (up to 4.7 times lower) when compared to the shod only, and shod with custom orthotic conditions. The differences between the shod only and shod only with custom orthotics were nominal (averaging only a 7.55% improvement in structural strength/stability and a 7.02% lower tension on the plantar fascia).

Introduction

From a strictly mechanical perspective, the lower limb structure is comprised of a ball and socket joint at the hip, a simple hinge joint at the knee, with the foot and ankle functioning similar to a ball and socket joint in order to provide an effective interface with the ground. (Figure 1)

When the structure is aligned properly, efficient locomotion through a multitude of three-dimensional movements over varied terrain is possible. The efficiency of this alignment is crucial to control of the body's center of mass with the lowest stress and susceptibility to injury. Ideally, the foot and ankle function analogously to a ball and socket joint while providing the stable foundation necessary for efficient and stress-free alignment up through the body's kinetic chain.

Figure 1

It is widely recognized that it is the shape of the interlocking bones and ligament strength that maintains the transverse, medial, and lateral longitudinal arches of the foot. [12, 13, 14, 15] This established viewpoint, while technically correct, overstates the role that bone shape and ligament strength play in maintaining optimal structural integrity of the foot. For example, if we isolate the bones of the foot from the muscle, tendons, ligaments, etc., and view the structure from a physics perspective, it becomes clear that the relative alignment and positioning of the bones is the primary determining factor in its structural capabilities. [12, 14, 16, 17, 18]

Within the medical community, the foot is commonly described as consisting of the medial, lateral, and transverse arches. [15, 19] This view, from a physics perspective, is inordinately simplified and ignores the complexity of the structure as a whole. The structural physics of the foot more accurately demonstrates a series of intersecting arches that run medially to laterally and posteriorly to anteriorly from the calcaneus to the metatarsal heads. (Figure 2)

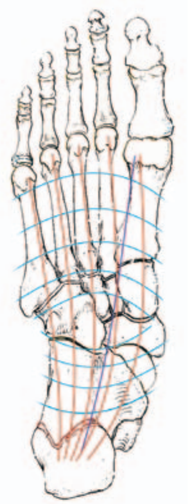


Figure 2

When combined in a multi-arch system, such as the foot, these singular arch dynamics work synergistically to maximize relative strength and stability while greatly minimizing stress, and are more effective collectively than individually.

Therefore, from a physics perspective, the most inherently sound structural mechanics would be achieved if the bones of the foot could interlock and maintain the multi-arch functional dynamics of a *dome* shape. Such a dynamic could manage greater loads with minimal contribution from, or stress on, the ligaments and extrinsic/intrinsic musculature. The dome shape created by the interlocking bones' would function much like a socket, capable of rotating around an imaginary ball. (Figure 3) The dome's level of functional stability would be determined by the "Ideal" or "Optimal Arch Apex" height necessary to most effectively maintain structural integrity in the interlocking bones as they

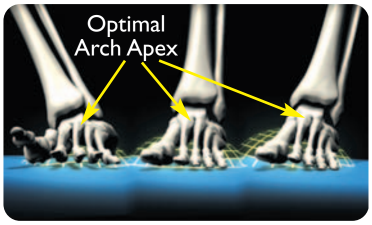


Figure 3

manage the forces generated throughout three-dimensional activity.

Previous research has shown that the relative positioning of the midfoot joints (the Optimal Arch Apex) is significant to the degree and pattern of forefoot segment motion, which in turn, is indicative of the foot's stability. [12, 16, 20, 21]

To better understand both the simplicity and complexity of this arch system, it is important to indentify the dynamics of a single arch and its intrinsic relationship within a system of arches.

In the foot, the structural mechanics of a single arch (Figure 4) are determined by its components:

- the material composition of the arch: interlocking bone structure and ligaments—their relative strengths (tensile, compressive, etc.) and elasticity, and
- a tie beam: soft tissue, i.e., tendons, muscles, fascia, etc.,—their relative strengths (tensile and elastic).

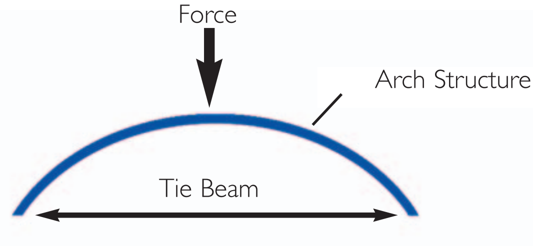


Figure 4

When force is applied to an arch structure, the stronger and more stable the material composition, the lower the degree of tensile (or pulling) force produced on the tie beam.

When comparing arches of identical composition with equivalent tie beam lengths, a higher arch is stronger and more stable and therefore generates less tensile stress (pulling force) on the tie beam. (Figure 5) The blue arch is twice as high (2a) as the red arch (a), therefore the relative traction (tensile) force of the blue arch is "a/2a" (or one half of the applied vertical Force at the arch apex). Mathematically, if the tie beam length was 10 units, and the height of the red arch was 2.5 units vs. 5 units for the blue arch, then the relative horizontal (tensile) stress component on the red arch tie beam would be 10/2.5 or 4 vs. 10/5 or 2 for the blue arch.

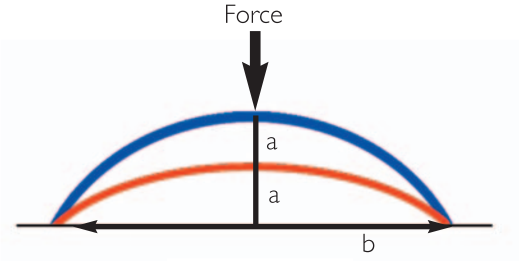


Figure 5

When this formula is applied to a single arch structure as seen in an individual foot with a fixed arch length (along the curve of the arch structure), it is clear that there is a direct relationship between a higher arch structure and a shorter tie beam. (Figure 6)

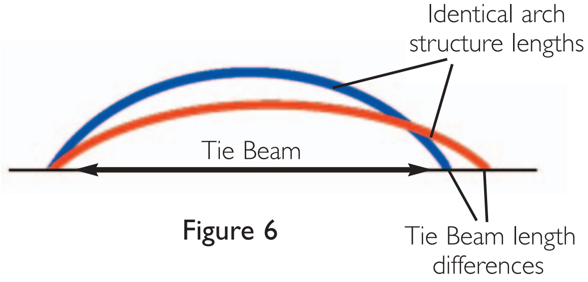


Figure 6

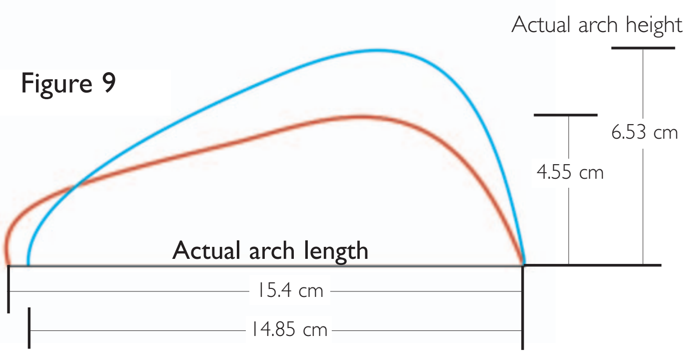
Despite their identical arch structure and tie beam components, the blue arch structure is not only proportionally stronger than the red arch structure (due to the increased height)—its strength is further accentuated by a decrease in its tie beam length. The increase in height, in combination with a decrease in tie beam length, is reflected in a significantly decreased tensile (pulling) force on the tie beam.

As is evident from the x-rays, the foot is capable of this functional dome-like alignment. (Figures 7 and 8) Both x-rays are of the same subject's right foot during full weight bearing. Traditional analysis of the subject's foot indicated typical hypermobility that in a relaxed stance (Figure 7) would be inclined to excessively pronate (as commonly described). The x-ray in Figure 8 was taken approximately ten minutes after the x-ray in Figure 7, with the great toe dorsiflexed (minimal effort).

Figure 7

Figure 8

Figure 9



The structural integrity of the arch system is determined by the arc created through the structure's center of mass. Figure 9 illustrates the actual differences in arch length and height. The length of the blue arch in Figure 8 is only 3.25% shorter than the red arch in Figure 7, with a relative 43% increase in height.

Figures 10 and 11 illustrate the geometry and mathematical equations for measuring: (a) the relative strength or vertical Force (F) capabilities of the arch, and (b) the Tension (T) in the tie beam during the single support phase, up to the point where the heel leaves the ground.

Consequently, the foot's structural alignment (single arch) in Figure 8 is capable of managing 50% (i.e., 210.9 vs. 141.0) greater weight or vertical force while generating 34.8% (i.e., 80.5 vs. 120.5) less tension on the tie beam, as seen in the equation for calculating plantar tension. [52]

Throughout the kinetic chain, the integrity of the foot's structural alignment plays a significant role in managing the forces and stresses generated during gait. [27, 34, 53, 54] It is clear that an ideal, dome-like structural alignment in the foot is possible, and that

Figure 10

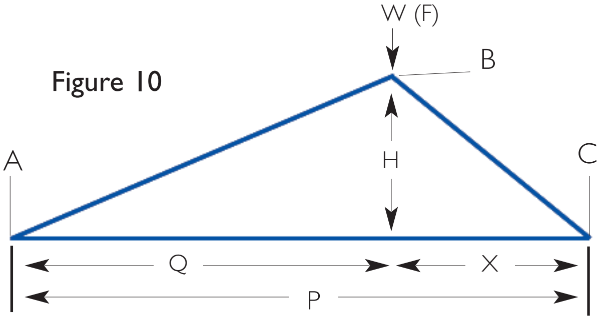


Figure 11

A = ball of foot
B = arch apex
C = heel ground contact

a) <u>RELATIVE ARCH STRENGTH</u>

$F = THP/QX$

T = tensile strength of tie beam (100 ft. lbs.)

F = W

b) <u>RELATIVE TIE BEAM TENSION</u>

$T = W(Q/H)\ (X/P)$

W = weight (170 lbs.)

Foot in Figure 7 (red arch):

a) $F = (100 \times 4.55 \times 15.4)/(10.8 \times 4.6)$
$F = 141.0$

b) $T = (170)\ (10.8/4.55)\ (4.6/15.4)$
$T = 120.5$

Foot in Figure 8 (blue arch):

a) $F = (100 \times 6.53 \times 14.85)/(10.45 \times 4.4)$
$F = 210.9$

b) $T = (170)\ (10.45/6.53)\ (4.4/14.85)$
$T = 80.5$

there is an inverse relationship between the structural integrity of the foot and the muscular effort required to facilitate and manage its relative alignment. The *more* structurally sound the arch, the *less* muscular effort is required to manage alignment.

Materials and Methods

A pilot study was undertaken to examine the relationship between arch height and length relative to dorsiflexion of the great toe during full weight bearing. Photographic measurement and X-ray protocols were developed to determine the changes in structural alignment due to increased dorsiflexion of the great toe, and the mechanical relationship between reduced foot length and arch height. These protocols were also used in identifying and comparing the relative structural changes as seen when barefoot and when wearing footwear only; and when wearing the same footwear with orthotics and a proprioceptive insole device.

The study consisted of twelve subjects that had used the proprioceptive insole device for at least two months (to allow for a soft tissue adaptation period). The subjects presented foot types in the following proportions: three flat (inflexible, pes planus), seven normal (two hypermobile), and two high arch (rigid, pes cavus). Reference points were marked on the subjects' skin surface, and relative distances were measured between points. Arch length and height were measured externally, both with the foot relaxed, and with the great toe dorsiflexed. The averaged results show a 2.88% decrease in arch length with the great toes dorsiflexed.

A fixed camera position was used to take multi-angle photographs of structural positioning changes in the subjects' feet and lower legs during full weight bearing. (Figures 11 & 12)

Three subjects were selected from the group of twelve for a series of foot x-rays—one from each of the following foot types: high arch (Subject one—rigid, pes cavus), normal (Subject two—hypermobile) and flat (Subject three—inflexible, pes planus). Images were taken of their feet when relaxed, and with the great toe dorsiflexed—barefoot and shod—with and without a proprioceptive insole device. X-rays were also taken of their feet, barefoot and shod, with and without custom orthotics and other insole devices.

To determine the relative structural positioning mechanics from the reference point measurements, the x-ray and photographic images of the medial side of the foot were digitized, combined, and scaled

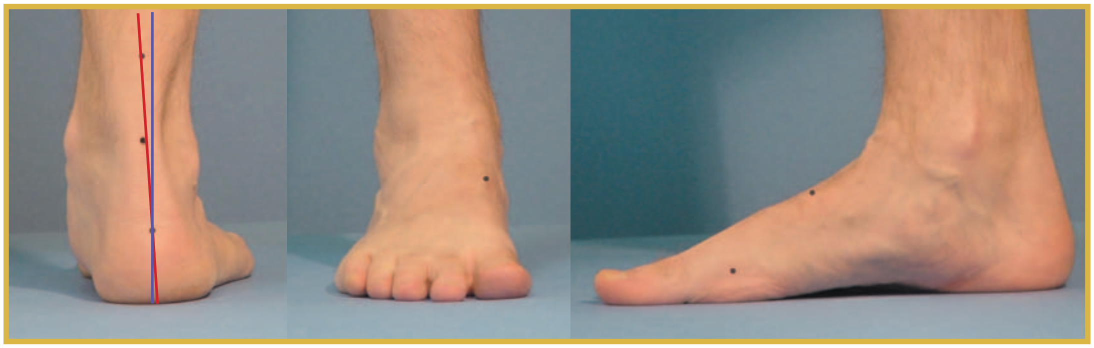


Figure 11 Relaxed

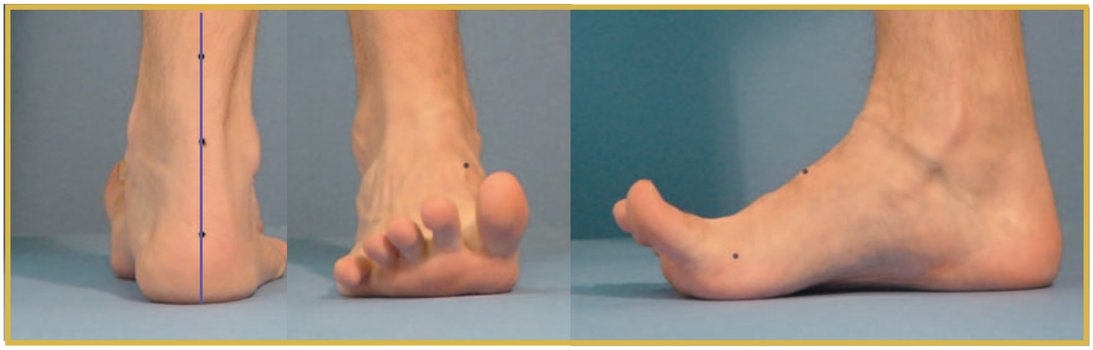


Figure 12 Great toe dorsiflexed (subject two)

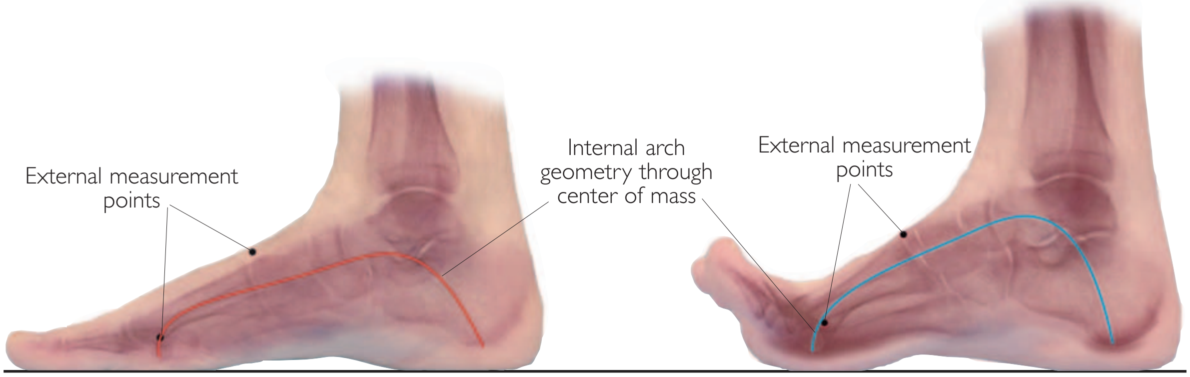


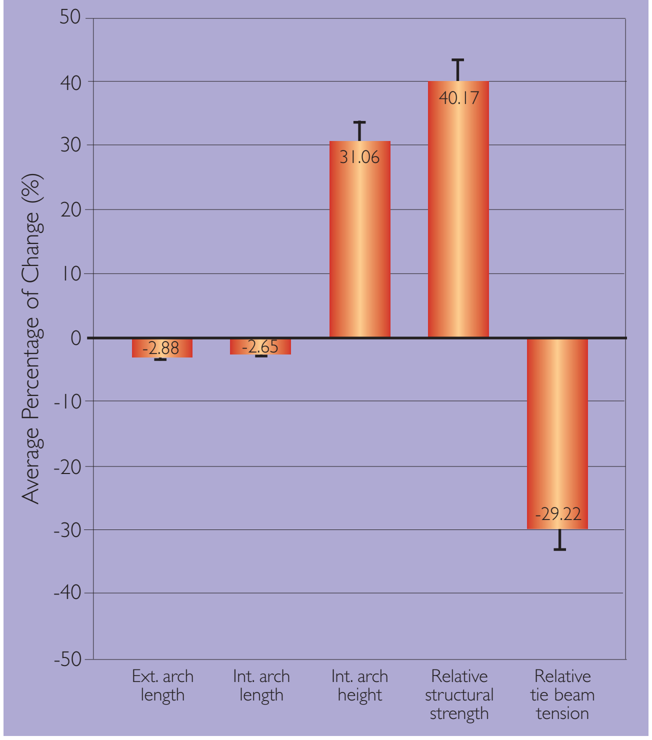
Figure 13 Arches created through center of mass (subject two)

to actual size using Adobe Photoshop software. (Figure 13) Accurate internal structural measurements were then taken of the skeletal arch geometry (through the center of bone mass) and were compared to the external arch height and length measurements.

The data for the three x-ray test subjects was averaged into percentiles of internal and external structural change and factored into data collected from each of the foot type groups. (Figure 14) The averaged results indicated that for each 1% decrease in arch length, the internal arch height correspondingly increased by 10.78%. The internal structural geometry changes of the x-ray group were also averaged into the Relative Arch Strength and Relative Tie Beam Tension equations. The results indicate a 1.2% increase in arch strength for every 1% increase in internal arch height.

Given the same loads, with the great toe dorsiflexed, the test group's structural geometry averaged a 40.17% increase in relative arch strength, while tension in the plantar fascia decreased by 29.22%.

Figure 14 Average Arch Length and Height Changes in Relation to Relative Foot Structure Strength



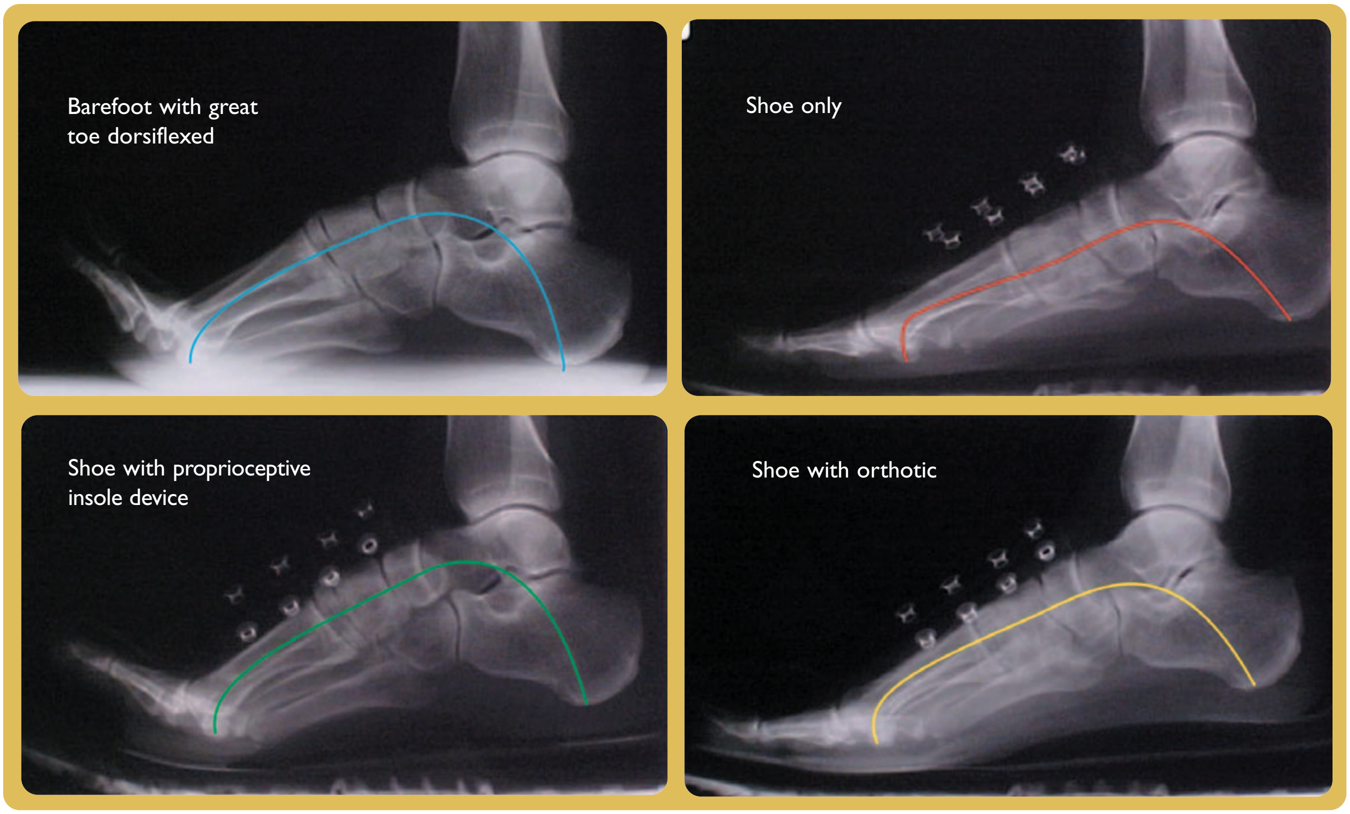


Figure 15

The structural alignment of the three x-ray subjects' arches through center of bone mass (Figure 15) were compared for four conditions:

1) barefoot—with the great toe dorsiflexed,
2) shod—regular footwear only,
3) shod—with a proprioceptive insole device (great toe dorsiflexed), and
4) shod—with a custom orthotic (posted to four degrees at rearfoot and six degrees at forefoot).

The resulting arch profiles were then grouped (Figure 16) and their geometric measurements entered into the Relative Arch Strength and Relative Tie Beam Tension equations. The percentage of change demonstrated in each condition, compared to the regular shod condition, is reflected in the accompanying graphs. (Figures 17, 18, 23, & 24)

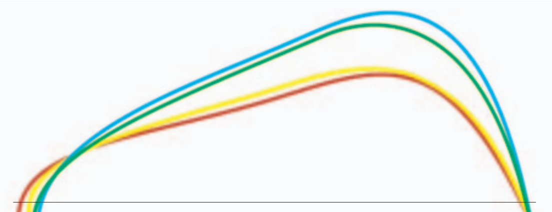


Figure 16

Results

In all instances, alignment improved when the great toes were dorsiflexed.

As expected, Subject one (rigid pes cavus foot) demonstrated the lowest degree of change in all conditions. (Figure 17) The "barefoot—with the great toe dorsiflexed" condition demonstrated an improvement in relative structural strength of 18.39%, and tie beam tension was reduced by 15.54%. The "shod—with the proprioceptive insole device" condition demonstrated an improvement in relative structural strength of 9.82%, and tie beam tension was reduced by 8.94%.

In identical footwear, this condition demonstrated a 4.2 times greater improvement in structural alignment, 3.3 times greater structural strength, and 3.1 times less tie beam tension when compared to the "shod—with a custom orthotic" condition, which demonstrated structural alignment changes (arch height increases) of 1.88%, structural strength increases of only 2.97%, and tie beam tension decreases of 2.88%.

Figure 17 Arch Length, Height, Tension, and Force % Change Relationships by Condition (Subject one - rigid pes cavus foot)

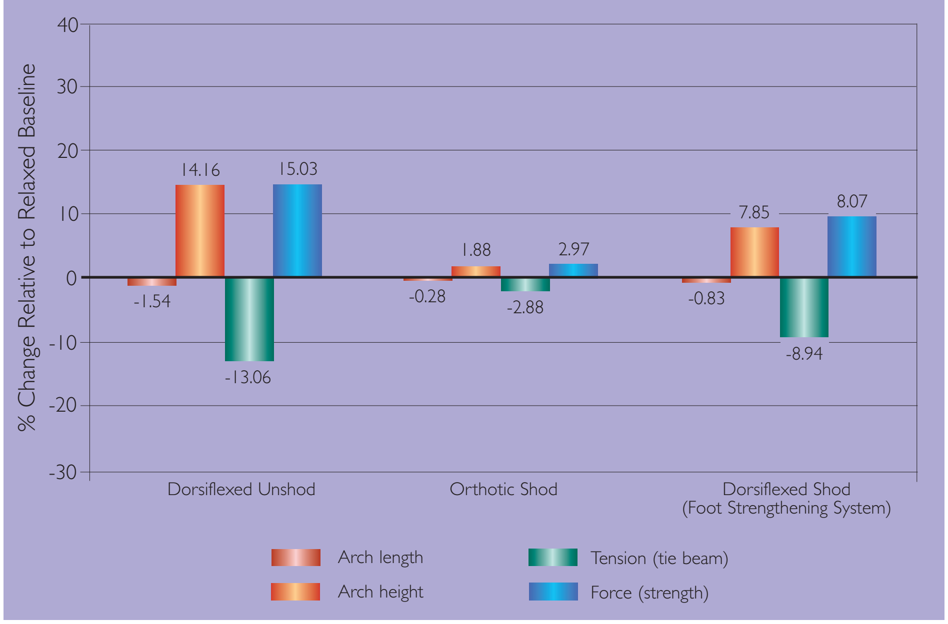
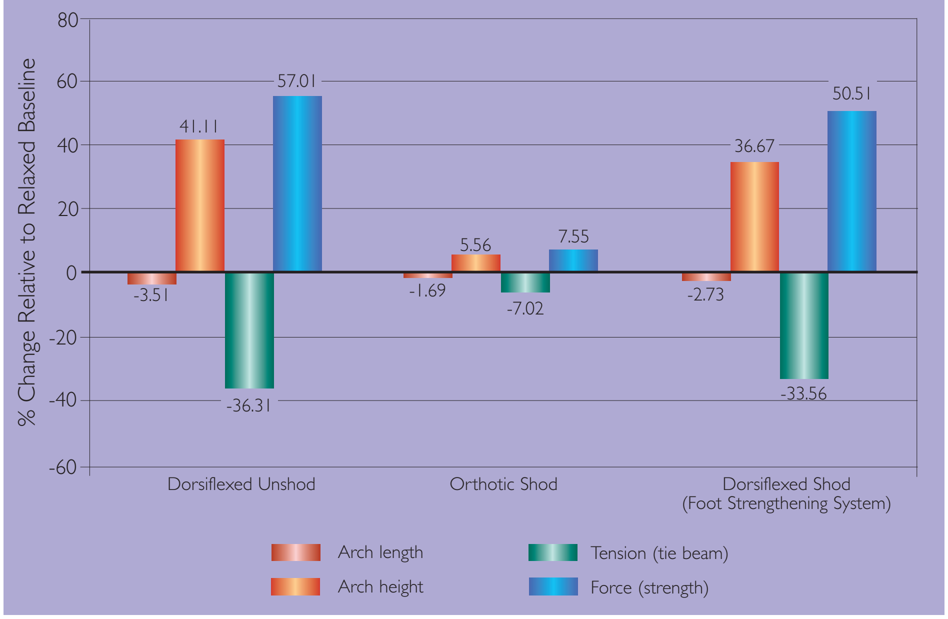


Figure 18 Arch Length, Height, Tension, and Force % Change Relationships by Condition (Subject two - normal hypermobile foot)



Subject two (normal hypermobile foot) demonstrated the greatest degree of change in the "barefoot—with the great toe dorsiflexed" and "shod—with the proprioceptive insole device" conditions. (Figure 18)

The "barefoot—great toe dorsiflexed" condition's relative structural strength improved by 57% and tie beam tension was reduced by 36.31%. The "shod—with the proprioceptive insole device" condition's structural strength improved by 50.5% and tie beam tension was reduced by 33.6%. In identical footwear, this condition demonstrated a 6.6 times greater improvement in structural alignment (arch height), 6.7 times greater structural strength, and 4.7 times less tie beam tension, when compared to the "shod—with a custom orthotic" condition, which demonstrated structural alignment (arch height) improvements of 5.56%, structural strength increases of only 7.55%, and tie beam tension decreases of 7.02%.

Subject three (inflexible pes planus foot) did not demonstrate a functional arch geometry through center of bone mass in either the relaxed barefoot or shod conditions. (Figure 19)

In order to compare structural strength and tie beam tension changes, a stable arch was assumed and relative geometric measurements were taken and incorporated into the Relative Strength and Tie Beam Tension equations. (Figure 23) With this considered, the "barefoot—great toe dorsiflexed" condition's relative structural strength improved by 21.75% and tie beam tension was reduced by 17.86%. The

Figure 19 Subject three (07/2001)

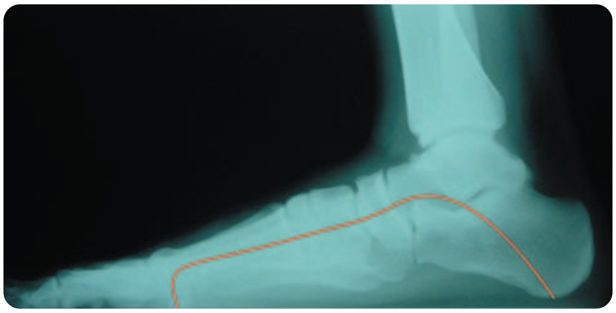


Figure 20 Subject three (02/2002)

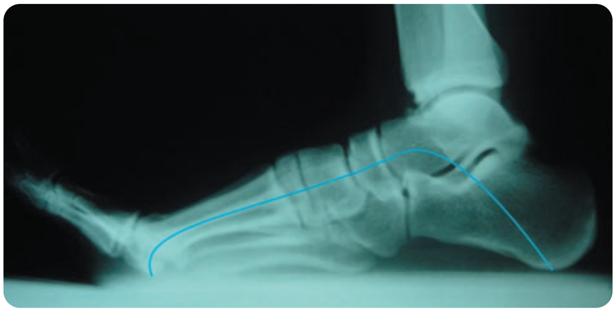


Figure 21 Subject three (07/2001)

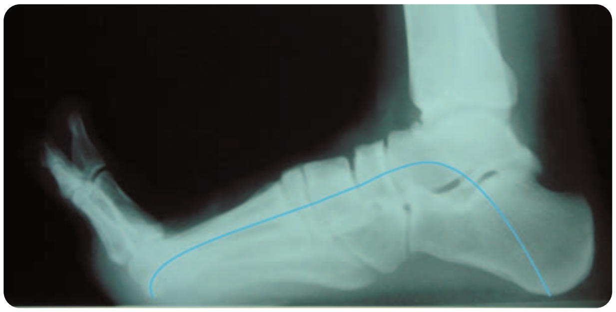


Figure 22 Subject three (02/2002)

“shod—with the proprioceptive insole device” condition’s structural strength improved by 15.22% and tie beam tension was reduced by 13.21%. In identical footwear, this condition demonstrated a 1.6 times greater improvement in structural alignment (arch height), 2.23 times greater structural strength, and 2 times less tie beam tension when compared to the “shod—with a custom orthotic” condition, which demonstrated structural alignment improvements (arch height) of 6.14%, structural strength increases of 6.82%, and tie beam tension decreases of 6.38%.

Subject three had used the proprioceptive insole device for the least amount of time and was still progressing though the device’s insert stages, therefore, follow-up x-rays and measurements were taken approximately six months later. (Figures 20 & 22)

When compared to those initially taken, these later x-rays clearly illustrate improved structural alignment and mobility. The structural alignment in the later weight bearing unshod condition (Figure 20) reflects a functional arch geometry (through center of bone mass). Great toe dorsiflexion improved from 33° (Figure 21) to 71° (Figure 22).

New structural geometry measurements were taken and incorporated into the Relative Strength and Tie Beam Tension equations. Significant improvements in structural strength, and reduced tie beam tension are demonstrated. (Figure 24) The “barefoot—great toe dorsiflexed” condition’s relative structural strength improved to 35% and tie beam tension was reduced by an additional 8.17%, to a total reduction of 26.03%. The “shod—with the proprioceptive insole device” condition’s structural alignment (arch height) improved from 10% to 17.05%, structural strength improved from 15.22% to 21.16%, and tie beam tension was further reduced to 17.47%. In identical footwear, this new condition demonstrated a 2.8 times improvement in structural alignment (arch height), 3.1 times greater structural strength, and 2.7 times less tie beam tension when compared to the “shod—with a custom orthotic” condition.

Discussion

Previous studies have demonstrated a clear relationship between the use of the proprioceptive insole device in footwear, and the proprioceptive muscle activation necessary to optimally align and stabilize the foot, prior to and during weight bearing ground

Figure 23 Arch Length, Height, Tension, and Force % Change Relationships by Condition (Subject three - inflexible pes planus foot)(07/2001)

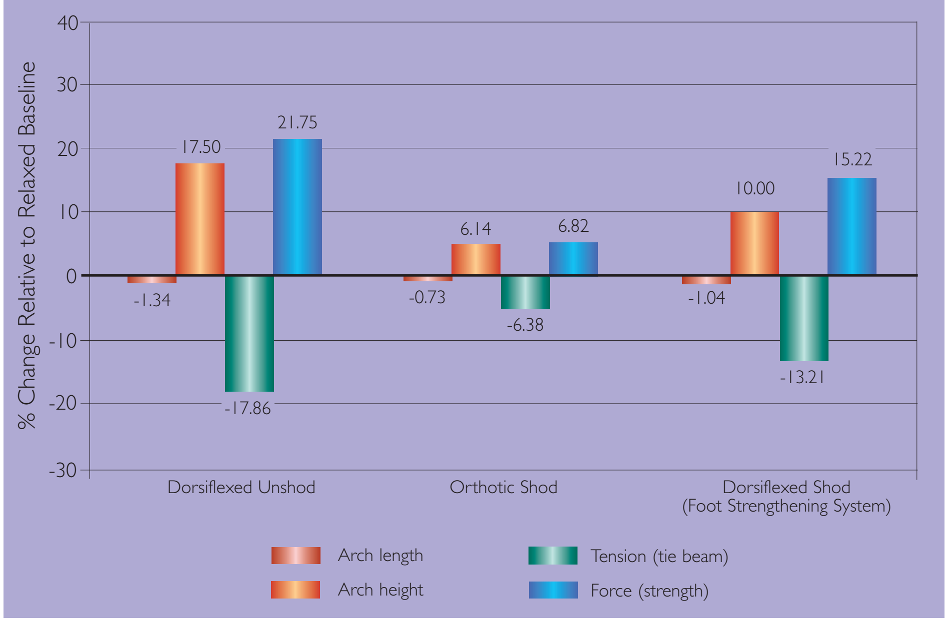
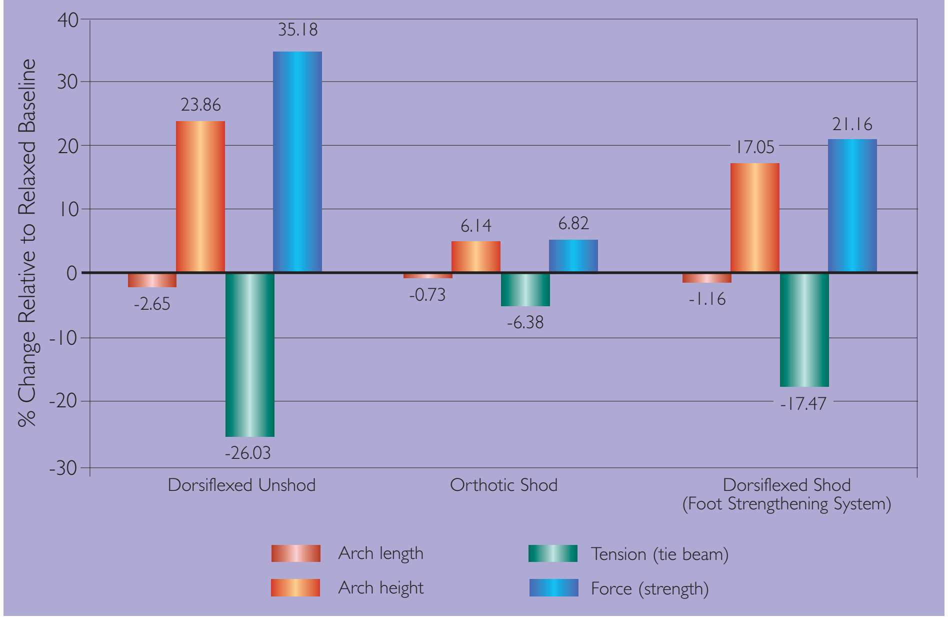


Figure 24 Arch Length, Height, Tension and Force % Change Relationships by Condition (Subject three - inflexible pes planus foot)(02/2002)



contact. Previous studies have also demonstrated that this muscle activation is a natural adaptive response to activity levels during barefoot gait, which is virtually eliminated during regular footwear use, with or without custom orthotics.

The findings of the previous research [1,2,3] combined with the findings described herein clearly indicate that in both the "barefoot" condition and the "shod—with the proprioceptive insole device" condition, the foot demonstrates a significant improvement in structural alignment and functional dynamics (greater strength and a reduction of unhealthy stress in the muscles and at joints), when compared to the "shod only" and "shod—with a custom orthotic" conditions. In addition, the "shod—with the proprioceptive insole device" condition provides a significantly greater degree of beneficial change to structural alignment through the foot, knee, and hip when compared to the "shod—with a custom orthotic" condition in identical footwear.

These combined findings provide compelling evidence that the benefits of the proprioceptive insole device are vastly superior to those of conventional orthotics. However, the data for the relative foot strength and horizontal plantar tension forces reflects only the arch formed by the alignment of the bones in the foot. The data does not incorporate the tensile forces generated by the muscles and tendons, stimulated through the adaptive proprioceptive muscle activation, which actually aligns and stabilizes the arch. It is logical to assume that these tensile forces would contribute significantly to a further strengthening of the foot's arch system. As this proprioceptive muscle activation is clearly not evident during the "shod only" or the "shod—with a custom orthotic" condition, any inherent arch would be correspondingly less stable.

Furthermore, the data indicates that the degree of restriction in toe box height, which prevents optimal great toe dorsiflexion, and over-the-arch apex (i.e. tight lacing, etc.), which prevents an optimal arch apex, has a corresponding impact on the foot's ability to form and maintain a stable arch system.

References

1. Burke R, Reyes R. Bompa T. Insole System Decreases Plantar Surface Area. BioMechanics 8(10); pp. 85-93, October 2001.
2. Burke R, Reyes R. A proprioceptive insole device's ("the Barefoot Science Foot Strengthening System") effect on the foot's structural mechanics.
3. Burke R, Reyes R. The effect of a proprioceptive insole device (the Barefoot Science Foot Strengthening System) on the foot's structural mechanics during varying activity levels.
4. Sethi PK. The Foot and Footwear. Prosthetics and Orthotics International 1: p. 173, 1977.
5. Tis LT, Higbie EJ, Chadwick L, Johnson BF. Put to the Test: Orthoses Reduce Pressure But Fall Short of Biomechanical Correction. Biomechanics.: October 2000.
6. Fuller EA. Reinventing Biomechanics. Podiatry Today: December 2000.
7. Miller M, McGuire J. Literature Reveals No Consensus on Subtalar Neutral. Biomechanics: p. 63, August 2000.
8. Orthotics - The Miracle Cure-All? Footwear News 51(19): p. 22, May 1995.
9. Nurse MA, Nigg BM, Deazeley S. Effects of Forefoot Posting on the Kinematics of the Lower Extremities During Walking. Human Performance Laboratory, University of Calgary
10. Edwards A. Interview: Foot and Ankle Research Drives Northern Arizona Practitioner. Biomechanics: p. 29, September 2000.
11. Baycroft C. Orthotic Devices and Foot Function. Patient Management: p. 115, June 1987.
12. Donatelli R. Normal Biomechanics of the Foot and Ankle. The Journal of Orthopaedic and Sports Physical Therapy 94: 1985.
13. Subotnick SI. The Flat Foot. The Physician and Sports Medicine. 9(78): p. 85, August 1981.
14. Perry J. Anatomy and Biomechanics of the Hindfoot. Clinical Orthopaedics and Related Research 177: p. 9, July/August 1983.
15. Moore K, Agur A. Essential Clinical Anatomy. Williams and Wilkens, Baltimore, Maryland, U.S.A., p. 254, 1995.
16. Hunt A, Smith R, Torode M, Keenen M. Inter-Segment Foot Motion and Ground Reaction Forces Over the Stance Phase of Walking. Clinical Biomechanics 16: p. 592, 2001.
17. Yessis M. Running Barefoot vs. Running in Shoes. AMAA Quarterly Spring 1998: p. 5
18. Doxey G. Calcaneal Pain: A Review of Various Disorders. The Journal of Orthopaedics and Sports Physical Therapy 9(1): p. 25, 1987.
19. Copeland G. The Foot Doctor: Lifetime Relief For Your Aching Feet. MacMillan Canada, A Div. of Canada Publishing Corp., 1996.
20. Tomaro JE, Burdett RG, Chadran AM. Subtalar Joint Motion and the Relationship to Lower Extremity Overuse Injuries. Journal of the American Podiatric Medical Association 86(9): p. 427, September 1996.
21. Latanza L, Gray GW, Kantner RM. Closed Versus Open Kinematic Chain Measurements of Subtalar Joint Eversion: Implications for Clinical Practice. The Journal of Orthopaedic and Sports Physical Therapy 9(9): p. 310, 1988.