Endnotes

* My apologies that this **First Draft** is in far less finished form than I would like, but I felt that its early release is warranted now, as is, obligated by the urgent need to start an expert debate on the critical medical issues raised herein. Those issues require urgent follow-on research at appropriate scale if correct, as is strongly suggested by the preliminary scientific basis I have provided.

Chapter 1 Introduction

1. Pardon the offensive language. I am just quoting this old study, which all too typically uses Colonial racist language of that era. The study also refers to the “natives” as “savages,” probably in shocked reaction to their headhunting and cannibalism, both still common practices in 1939 in the area of New Guinea.

Using more modern terms, the race of the natives would be considered Polynesian and that of the “Europeans” would be Caucasian. To be most correct today, you would just say that the two groups from different geographic areas have discernible genetic differences.

The study is **James**, Clifford S. (1939). Footprints and feet of natives of the Solomon Islands. In the ***Lancet***: 2: 1390-1393. Malaita, the island in the study, is next to Guadalcanal, site of famous U. S. Marine and Naval battles against the Japanese just a few years later in 1942 during World War II.

2. **Willwacher**, Steffen, Irena Goetze, Katina Mira Fischer and Gert-Peter Bruggemann. (2016). The free moment in running and its relation to joint loading and injury risk. In ***Footwear Science*** Vol. 8, No. 1, 1-11 particularly pages **4-9** and **Figures 4-6**. Winner of the **Nike Award for Athletic Footwear Research**, the highest award presented at the **XIIth Footwear Biomechanics Symposium** in Liverpool, UK 2015**.**

3. Another old study also shows in Figures below the shoe-wearing European heel bone tilted out in the unnatural supination position, compared to barefoot Africans. Note the level lines of the Achilles tendon attachment to the bone on all three samples, which shows the characteristic supination-based structural tilt to the outside in (**D**) European versus barefoot Africans (**B** & **C**).

Although less complete than the James Solomon Islands study, since it does not show the calcaneus of a European who has never worn shoes, it does show uniquely how the supinated or tilted out position is actually baked into the structure of the bone.

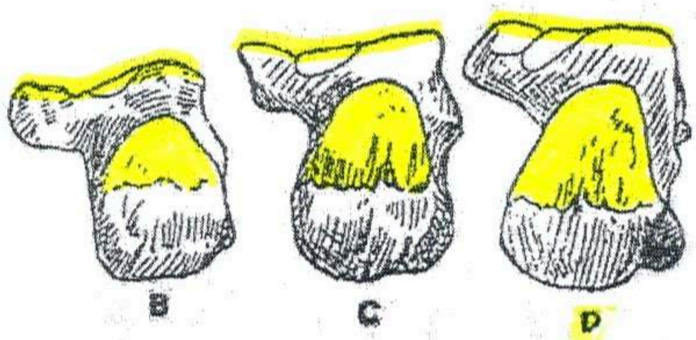

Fig. 6 Posterior aspect of the calcaneus of a Bushman (B) a Bantu (C) and a European (D) showing the differences in the slope of the articular facets and the projection of the sustentaculum tali.

FIGURE C Only the European Heel Bone (D) is in SUPINATED Position

FIGURE C from **Wells,** Lawrence H. (1931). The Foot of the South African Native. In ***the American Journal of Physical Anthropology***, Vol. XV, No. 2. 186-289, **Figure 6** on **page 225**. (Note: Fig. 6 is not modified, except by removing the non-human example (A) a baboon and by colorizing)

4. **Robbins**, Steven E. & Hanna, Adel M. (1987). **Running-Related Injury Prevention Through Barefoot Adaptations**. In *Medicine and Science in Sports and Exercise* 19, **148-156**.

5. **Marti**, Barnard et al. (1989). On the epidemiology of running injuries. In *The American Journal of Sports Medicine* 16: 3; 285-294, particularly pages **287** and 291.

6. **Bramble**, Dennis M. & **Lieberman**, Daniel E. (2004). Endurance running and the evolution of *Homo*. In ***Nature*** 432: 18 November 345-352. I find nothing to disagree with them relative to their discovery that humans evolved into a design optimized for endurance running, which made humans very successful predators. But in addition, I think it is obvious and old news that man also evolved to run fast, at least relatively so, in order to be successful as individual prey escaping from a predator. In that context, I cannot avoid recalling the very old joke about a brief conversation between two people being chased by a bear. One of the pursued observed aloud that he did not need to be faster than the bear, he only needed to be faster than the other person in order to survive. Also, see Lieberman, Daniel E. et al. (2007). The evolution of endurance running and the tyranny of ethnography: A reply to Pickering and Bunn (2007). In the *Journal of Human Evolution* 53: 439-442.

7. **Richards**, Craig et al. (2009). **Is Your Prescription of Distance Running Shoes Evidence-Based?** In *British Journal of Sports Medicine*, April. See also **Ryan**, Michael B. et al. (2011). The effect of three different levels of footwear stability on pain outcomes in women runners: a randomized control trial. In the *British Journal of Sports Medicine* 45: 715-

721, particularly page **715**.

8. **McDougall**, Christopher (2010). ***Born To Run****. New York: Alfred A Knopf.* The entire book is a fabulous read, but I recommend particularly Chapters 25 and 28, which provide much more detail on the research I cited by Robbins, Marti, as well as Bramble and Lieberman. See also his article on "**The painful truth about trainers: Are running shoes a waste of money?** at Mail Online: www.dailymail.co.uk/home/moslive/articl1170253/The-painful-truth-trainers-are-expensive-running-shoes-waste-money.html. See also: "**New Study by Dr. Daniel Lieberman on Barefoot Running Makes Cover Story in *Nature* Journal**" at www.runbare.com/389/new-study-by-dr-daniel-lieberman-on-barefoot-running-makes-cover-story-in-nature-journal/. In addition, see "**The Once and Future Way to Run**" at www.nytimes.com/2011/11/06/magazine/running-christopher-mcdougall,html/?_r=2&ref=nutrition.

9. I am not counting Nike Free™ shoes here because I think it is questionable to call them a barefoot-based sole design. They are really just conventional shoe soles with a newly modified use of a very old technology: relatively deep slits (called "sipes") in the soles to create better flexibility that is more like the natural flexibility of the human foot sole. Nike Free™ also came out earlier, in 2004. That technology is largely a newly modified adaptation of the 1930's boat shoe design with siped soles for traction that were made commercially popular as the Sperry Topsider™, which is still popular today.

A recent study confirms my earlier evaluation that Nike Free™ shoes "failed to result in changes in spatio-temporal parameters when compared with running in a standard running shoe". From page 1201 of: **Squadrone**, Roberto et al. (2015). Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. In *Journal of Sports Sciences*. 33: 11: 1196-1204.

By the way, in point of indisputable fact, I invented the flexible sole with slits technology for athletic shoes in 1989 and filed U. S. and international patent applications covering the technology at that time. Both U. S. and international applications were published in their entirety several times internationally, beginning in 1991.

I came up with the simple design because I had very limited funds at that time. Back then when I was just being started in barefoot-based design I had only a very limited, jury-rigged prototyping capability. So conventional soles with deep slits for better flexibility at least more like the barefoot sole was the only cheap and easy approach available to me to make decent prototypes for real world testing.

When I tested them, I became very disatisfied with my self-testing results, so I quickly developed a far superior design in which the slits are all completely within the shoe sole, which yields far better results, especially in terms of closely following the natural design of the extremely flexible human foot sole. That design, plus further improvements later in 2005-6, were developed and patented years ago, but no footwear companies are using these designs as far as I know, even though most of the earlier designs are no longer under patent protection, since the terms of the patents have expired.

10. **Hollander**, Karsten (2015). Comparsion of Minimalist Footwear Strategies for Simulating Barefoot Running. In *PLOS ONE* DOI: 10: 1371/journal.pone.0125880 May 26

11. **Shorten**, Martyn (2005). Footwear Biomechanics: What Does the Future Hold? *The 7th Symposium on Footwear Biomechanics* of the Technical Group On Footwear Biomechanics of the International Society of Biomechanics.

12. **Nigg**, Benno M. (2010). *Biomechanics of Sports Shoes*. Calgary, Alberta.

13. **Frederick**, E. C. (2011). Starting Over. In *Footwear Science* 3: 2: June 69-70.

14. **Bachman**, Rachel (2014). Better Than Barefoot. In *The Wall Street Journal*, July 23, D1 & D3.

15. **Ryan**, Michael (2014). Examining injury risk and pain perception in runners using minimalist footwear. In *British Journal of Sports Medicine* 48::1257-1262, especially pages 1 & 5.

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Properties, Mileage, or Shoes? In *Exercise and Sport Sciences Reviews* 40: 2: 59-**60**.

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See also **Relevant Foot Research** at Natural Footgear:
http://www.naturalfootgear.com/Relevant_Foot_Research.html

Chapter 2. ELEVATED SHOE HEELS TILT THE FOOT OUTWARD

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2. **Kolker**, Lionel (1972). A Biochemical Analysis of Flatfoot Surgery. In Modern Therapeutic

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3. **Evans** (adapted from Hicks). See also **Hicks**, J. H. (1961) The Three Weight-Bearing Mechanisms of the Foot. In Chapter 7 in *Biomechanical Studies of the Musculo-Skeletal System*. F. Gaynor Evans (ed.) Springfield, Illinois: Charles C Thomas, 161-191, especially pages **175-177**. And **Hicks**, J. H. (1954). The Mechanics of the Foot II. The Plantar Aponeurosis and the Arch. The *Journal of Anatomy*, 25-30, especially p. 27-**29 with Fig.** 1-**4**. In addition, **Sarrafian**, Shahan K & Kelikian, Armen S. (2011). Functional Anatomy of the Foot and Ankle. In *Sarrafian's Anatomy of the Foot and Ankle*. Third Edition, Armen S Kelikian (ed.) Philadelphia et al: Wolters Kluwer et al, 507-643, especially pages 511, 512, 516, 519, **560** with **Fig. 10.82**, 593-**594** with **Figs. 10.142 & 10.143**, and **620** with **Fig. 10.183**.

4. Barkema, Danielle D. et al. (2012). Heel height affects lower extremity frontal plane joint moments during walking. In *Gait & Posture* 35: 483-488, particularly pages 483, 485-487 with Figures 2 & 4. See also Cronin, Neil J. (2014). The effects of high heeled shoes on female gait: A Review. In the *Journal of Electromyography and Kinesiology* 24: 258-263. particularly pages 258 and 261.

5. **Foster**, Alicia et al. (2012). The Influence of Heel Height on Frontal Plane Ankle Biomechanics: Implications for Lateral Ankle Sprains. In *Foot & Ankle International* 33: 64-69, particularly pages 64, **67 with Table 1** and **Figure 3B**, and 68.

6. **Kouchi**, Makiko & Tsutsumi, Emiko (2000). 3D Foot Shape and Shoe Heel Height. In *Anthropological Science* 108: 4: 331-343, particularly page **331**, 336-338 with **Figures 5-7**, and **342**. **Stefanyshyn** et al. (2000), The Influence of High Heeled Shoes on Kinematics, Kinetics, and Muscle EMG of Normal Female Gait. In the *Journal of Applied Biomechanics* 16: 309-319, particularly pages 309, 313-316. See also **Hong**, Wei-Hsien et al. (2013). Effect of Shoe Heel Height and Total-Contact Insert on Muscle Loading and Foot Stability While Walking. In *Foot & Ankle International* 34: 2: 273-281, particularly pages **273**-274, 276-**277** with **Figure 3(b**), and 279 with Figure 5.

7. **Derrick**, Timothy R. et al. (2002). Impacts and kinematic adjustments during an exhaustive run. In *Medicine and Science in Sports and Medicine* 998-1002, particularly pages **998** and 1000-**1001 with Table 2**. See also **Clarke,** T. E. et al. (1983). The effects of shoe design parameters on rearfoot control in running. In *Medicine and Science in Sports and Exercise* 15: 5: 376-381, particularly page **377 with Fig. 1**.

8. **Ehlen**, Kellie A. et al. (2011). Energetics and Biomechanics of Inclined Treadmill Walking in Obese Adults. In *Medicine and Science in Sports and Exercise* 1251-1259, particularly

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Ebbeling, Christine J. et al. (1994). Lower Extremity Mechanics and Energy Cost of Walking in High-Heeled Shoes. In the *Journal of Orthopaedic and Sports Physical Therapy*19:4: 190-196, particularly page 195.

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van Gent, R. N. et al. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systemic review. In the *British Journal of Sports Medicine* 41: 469-480, particularly page **469**.

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See also **Relevant Foot Research** at Natural Footgear:
http://www.naturalfootgear.com/Relevant_Foot_Research.html

Chapter 3. SHOE HEELS ALSO TILT THE KNEE OUTWARD, ABNORMALLY RESHAPING THE CRITICAL JOINT

1. **Rubin**, Gustav (1971). Tibial Rotation. In *Bulletin of Prosthetic Research-Spring* 1971, 95-100, especially pages **96-97**. And Inman, Verne. T. (1976). *The Joints of the Ankle*. Baltimore: The Williams & Wilkins Company, particularly pages 35-38 with Figures 9.1-9.3, 39-40, 51-**53** with **Figure 10.12** and 54-**55**, as well as 57-**66** with **Figure 11.14**.

2. With regard to the static **coupling** mechanisms that are old and "settled science", among the oldest representative example references is Merton **Root**, John **Weed**, Thomas Sgarlato, and Daniel Bluth (1966). Axis of Motion of the Subtalar Joint. In the ***Journal of the American Podiatry Association*** 56: 4: pages 149-155.

With regard to Ned's reference to recent **decoupling** studies, see for example **Nigg**, Benno M. (2010). ***Biomechanics of Sports Shoes***. First Edition. University of Calgary: Calgary, Alberta, Canada. **Pages 80-93** have a relatively recent summary on ankle joint coupling between the foot heel and lower limb, as well as cited references on pages 123-129, with added references on pages 129-136. See also, Alex **Stacoff**, Benno Nigg, Christoph Reinschmidt, Anton Bogert, Arne Lundberg, Edgar Stussi, and Jachen Denoth (2000). Movement Coupling at the Ankle During the Stance Phase of Running. In ***Foot & Ankle International*** 21:3 pages 232-239, particularly **page 232** and **Fig. 5**.

Another good summary: Alison T. **DeLeo**, Tracy Dierks, Reed Ferber, and Irene Davis (2004). Lower extremity joint coupling during running: a current update. In ***Clinical Biomechanics*** 19 (2004) 983-991. A recent coupling reference: Katina M. **Fischer**, Steffen Willwacher, Joseph Hamill, and Gert-Peter Bruggemann (2017). Tibial rotation in running: Does rearfoot adduction matter? In ***Gait & Posture*** 51: pages 188-193. These are samples among many other decoupling studies.

The latest and probably most accurate study on running decoupling: Katrina Mira **Fischer**, Steffen Willwacher, Anton Arndt, Peter Wolf and Gert-Peter Brueggemann (2017). Calcaneal adduction in slow running: three case studies using intracortical pins. ***Footwear Science***, Vol. 9, no. 2, 87-93, particularly **Figure 1, page 88,** and **Table 1, page 90**. Note that a related study is on pages 79-85 of the same ***Footwear Science*** reference by Mattieu Trudeau, Carl Jewell, Eric Rohr, Katrina Mira Fischer, Steffen Willwacher, Gert-Peter Brueggemann, and Joseph Hamill. The Calcaneus adducts more than the shoe's heel during running.

3. A few months ago, I sent a copy of the first draft of the full book version of this article to E. C. "Ned" Frederick, Ph.D., for a preliminary review. Dr. Frederick has for many decades been one of the best-known scientists in the field of footwear biomechanics and is the former head of R&D at **Nike** (actually the first) and currently the Editor (also the first) of **Footwear Science**. He also played a significant role in helping to license my barefoot-based shoe sole technology to **Adidas** in the 1990's, where it became **Adidas'** core footwear technology for many years (See www.AnatomicResearch.com.)

Ned was kind enough to provide a quick and dirty analysis of my relatively long and complex first draft of a book (including over 50 pages of Endnotes), of which I believe the most important concern he raised was the decoupling issue. Although the static lower leg bio-mechanisms described in **FIGURES 2.3A&B, 2.4, 2.5A&B, 3.1, 3.2B, & 3.4A** are old and settled science, many studies in recent decades indicate clearly that these well-known static mechanisms are "**decoupled**" when running, as shown in the studies cited in Endnote[2] above.

I was already aware of many of these studies, but had not specifically addressed the issue in my draft book. In the course of my research I had interpreted the known running decoupling effect to be implicitly supporting the opposite conclusion, but had not formally presented my position explicitly. My personal thanks to Ned for taking the time to raise this important but unresolved issue so it can be directly addressed and emphasized as it should be.

So, in reaction to the issue constructively raised by Ned, I set out to find better research support for my opposite conclusion. Fortunately, I found it almost immediately in data from the earlier cited study by Steffen **Willwacher**, Irena Goetze, Katina Mira Fischer and Gert-Peter Bruggemann.

The study is titled "The free moment in running and its relation to joint loading and injury risk," in ***Footwear Science*** (2016), Vol. 8, No. 1, pages 1-11 particularly pages **4-9** and **Figures 4-6**. The study is the winner of the **Nike Award for Athletic Footwear Research**, the highest award presented at the **XII^th^ Footwear Biomechanics Symposium** in Liverpool, UK 2015, a biannual conference sponsored by the **International Society of Biomechanics.**

What I found was that with some formal analysis the actual physical existence of the artificial decoupling shoe heel bio-mechanism can be proven mathematically using the unusually large data set from the **Willwacher** study**.** The proof is surprisingly solid. It is slightly technical, but you can see a summary of the full analysis below.

Simple Mathematical Proof that Shoe Heel-Induced Foot Supination Causes Joint

Decoupling - Provided by Data from the Willwacher Study and Rubin Study:

The Rubin study on supination of barefeet found using analogue modeling that for every 1° of supination, the tibia is rotated outward (or externally) by about 1.7°, a ratio of 1:1.72. This is an inherent, automatic linkage that happens strictly by the mechanical interaction of biological parts, principally the shin bone, the ankle bone, and the heel bone, as well as the main foot sole ligament (that is, the tibia, talus, and calcaneus, as well as the plantar aponeurosis).

More precisely, this **direct coupling** between shoe heel-induced subtalar joint supination and tibial outward rotation is strictly bio-mechanical. It is therefore just as inevitable as if it were a direct mechanical interaction of gears. It is strictly automatic.

It is in fact the closest biological equivalent of a strictly mechanical interaction between parts. But, like the automatic mechanical interaction of a multitude of relatively simple geometric parts of a clock, this is an automatic interaction of a much more limited number of human bone parts, all with far more complex, non-geometric anthropomorphic shapes.

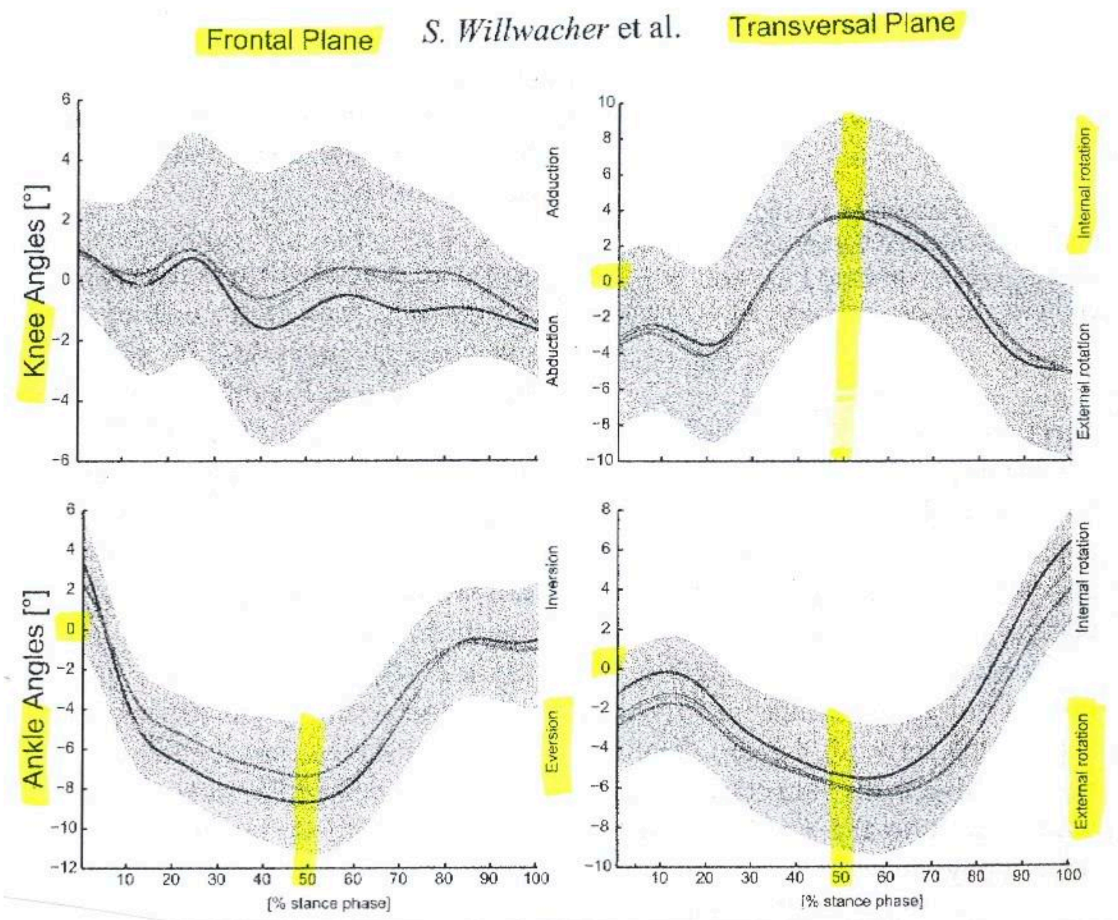
The Ankle Angle Frontal Plane graph of Figure 6 of the Willwacher award-winning study shows ankle eversion (effectively identical to pronation) of about **11°** for the average of all 222 runners under a maximum body weight load at midstance while wearing their own mostly conventional running shoes. See **Selected Willwacher et al. Graphs** below.

According to the Rubin study ratio of 1:1.7, the **11°** of inward rotating **ankle** eversion should be directly coupled with fully **18°** of internal rotation of the tibia (and knee joint). Instead, in the Knee Angle Transverse Plane graph of Figure 6 of the Willwacher award-winning study, there is only **8°** of internal rotation of the **tibia (and knee joint)**, fully **10°** less that should be there according to **Rubin's Ratio of 1:1.7**.

The Mysterious Missing 10° of Inward Tibial Rotation

This is an important mystery. Why is the **10°** missing? Less than half as much inward tibial rotation occurs in Willwacher's testing when running in shoes compared to Rubin's static testing of barefeet modeling.

The only available explanation is the outward rotation of unnatural supination caused by the shoe heel coupling effect carefully described by Rubin! Simply put, unnatural shoe heels must cause the abnormal joint motion decoupling.



Selected Graphs from Figure 6 of the Willwacher et al. Study (2016)

This **10°** discrepancy indicates clear evidence of a very substantial **decoupling** during running in shoes of the directly parallel linkage between ankle and tibia rotation found in Rubin's stationary study of barefeet.

In fact, the substantial decoupling shown in the Willwacher study provides clear proof of the direct mechanical effect of shoe heel-induced supination on knee motion in the transverse plane. The inescapable conclusion is that the shoe heel-induced unnatural supination actually causes the abnormal decoupling, which is otherwise inexplicable (or simply magic), as it has remained until now!

The math is simple. The missing **10°** of inward tibial rotation is a result of **10°** of outward rotation that must be caused (using Rubin's Ratio of 1:1.7) by about **6°** of shoe heel-induced supination, about as expected by our previous analysis of shoe heel-induced supination. The two equal tibia rotations of **10°** in opposite directions cancel each other out, leaving the observed net inward tibia rotation of only **8°** when running in shoes.

No studies currently exist that have measured unloaded foot supination with shoes of varying heel heights in the midstance running position of about **20°** dorsiflexion, so the apparently observed **6°** of shoe heel-induced supination is not validated by other studies. However, the results of many well-established studies have indicated that the unloaded landing position of the foot range from about **2°** (Willwacher) to about **8°** (Cavanagh), so the above result of about **6°** is reasonable.

(Furthermore, as discussed in a few more pages, Willwacher's test subjects are outliers, middle-aged "survivor" runners, not typical runners. So, it is likely that their foot position is closer to neutral than is the norm, making it reasonable to discount his low **2°** result in favor of something closer to the higher **6°** result that we computed from the data.)

Additional support comes from the earlier discussion of **FIGURES 1 A&B**, wherein the standing position Willwacher's test subjects' feet average was **4-5°** of inversion/supination. This measurement was made while standing in their own running shoes, which were unidentified but typically today have heels lifts of about **6-10 mm**.

Thus, the observed **11°** of foot eversion (or pronation) is a net composite of what must actually consist of about **5°** natural pronation and about **6°** of additional, unnatural pronation that compensates directly for the about **6°** of artificial shoe heel-induced supination.

The easiest way to understand this odd result is that, essentially, the runner's foot is pronating in an excessive, additional amount to compensate for the artificial effect of the shoe heel, which has unnaturally rotated the foot outward into an abnormal supination position.

That final result neatly proves mathematically the existence of a direct bio-mechanical decoupling effect of shoe heel-induced ankle joint supination and its directly resulting tibial external rotation, based on the **Willwacher** prize-winning study, which is particularly authoritative because of its exceptionally large and therefore more statistically valid sample size than is typical of running studies (222 runners)!

Reservations About This Convenient Mathematical Proof

When I reviewed all the joint coupling running studies cited above in Endnote[2], I noticed that none of them cite Gustav Rubin's static study nor seem to be aware of it. For example, the Stacoff et al. study assumes "a theoretical 1:1 coupling from the calcaneus to the tibia" relative to its Figures 4 & 5, whereas Rubin's Ratio is 1:1.72. That is nearly 1:2, not 1:1.

The Stacoff empirical result during running was 1.72, or nearly two degrees of ankle eversion for every one degree of internal tibial rotation. Astonishingly, this is exactly the opposite of Rubin's stationary result of nearly two degrees of tibial rotation for every one degree of foot supination (which biomechanically involves nearly the same amount of rearfoot eversion).

The DeLeo et al. study cites the results from all the relevant joint coupling running studies (through 2004) and all have similar ratios showing more or substantially more ankle eversion than tibial rotation during running. Again, roughly the polar opposite of Rubin's result.

The results summarized by DeLeo vary widely, from 1.0 to 2.2, because ankle joint coupling is inherently quite difficult to measure accurately for subjects who are running. In stark contrast, it is very easy to do accurately to develop accurate analogue models for subjects who are stationary, so it is hard to doubt the accuracy of Rubin's results.

This gross mismatch in results should have attracted considerable attention years ago, but apparently has been overlooked because Rubin's study itself has been overlooked. What accounts for the gross mismatch in results? More critically, which one is right?

Problems with the Classic Studies on the Subtalar Joint Axis

The decoupling studies that are cited in Endnote[2] mostly base their reasonable but assumption of a 1:1 ratio of motion between calcaneus and tibia on the **equidistant 45°** inclination angle for the subtalar joint axis in the sagittal plane found in the **Root** et al. study of cadaver feet.

In contrast, Rubin uses a slightly lower **41°** inclination angle, which may be slightly more accurate, but more significantly also used a **23°** angle (offset medially) in the transverse or horizontal plane to construct an analogue model (this later adjustment was not used by Verne **Inman** in the analogue modeling described in his classic, ***The Joints of the Ankle***. The Williams & Wilkins Company: Baltimore, 1976)

However, even without considering Rubin, the assumption is questionable, since an actual study of a small number of living test subjects by A. **Lundberg** found a mean subtalar joint inclination angle of **32°**, not **45°**. See "Kinematics of the ankle and foot". ***Acta Orthop Scand Suppl*** **60**: 1, 1989. (See also an excellent discussion of this assumption by Irene McClay (Davis) in "The Evolution of the Study of the Mechanics of Running" (2000) in the ***Journal of the American Podiatric Medical Association*** **90**: 3: 133-148, especially **page 144**, column 1.)

The Root et al. study was conducted on freshly amputated feet, dissected to bone and ligament alone. This difference may be important, since the dissected feet of Root were unloaded, whereas the living feet studies by Lundberg were presumably loaded by roughly ½ of the body weight of test subjects. A later study by E.J. **Van Langelaan** on loaded cadaver feet had results close to Rubin's joint axis angles, in: "A kinematical analysis of the tarsal bones." ***Acta Orthop Scand Suppl***. 1983: 204:1-269.

Much Better Rearfoot Measurement Parameters Have Been Demonstrated

Cited last in Endnote[2], the latest and possibly best running decoupling study is by Katrina Mira **Fischer** et al. because it makes a strong case that rearfoot motion in the horizontal (transverse) plane provides a more accurate basis for measuring the coupling of foot and lower leg motion during running than rearfoot motion in the frontal plane. That is to say, calcaneal adduction rather than calcaneal eversion, as shown in their **Figure 1** on **page 88**, is strongly coupled with tibial rotation.

Their barefoot running study yielded results of an observed average of **7.8°** of calcaneal adduction for an average of **12.1°** of internal tibial rotation - a **Fischer running coupling ratio** of calcaneal to tibial motion of **1:1.55**.

That Fischer running coupling ratio is nearly the same as the **Rubin static coupling ratio of 1:1.72** that was cited in Endnote[1] and illustrated in **FIGURE 3.1.** Since Rubin's study measured foot supination and pronation, the similar results between the running and static ratios points to the conclusion that measuring calcaneal adduction tracks foot supination and pronation much more accurately than does calcaneal eversion.

This conclusion is further reinforced in the barefoot Fischer study, wherein the observed average of **4.7°** of calcaneal eversion for an average of **12.1°** of internal tibial rotation yields a ratio of **1:2.57**, a far higher ratio than the shod coupling studies cited above in Endnote[5].

All of the Ankle Joint Coupling Studies Have Serious Shortcomings

However, important factors unique to running have not been accounted for in any of these studies. For starters, the load on the foot and ankle joint in running is 4-6 times greater than a loaded cadaver foot with a simulated walking load of ½ body weight. And at room temperature cadaver feet are much colder and less flexible than living feet.

Both factors are going to significantly depress the longitudinal arch height of the living foot when running compared to tested cadaver feet, so that the subtalar joint axis is likely going to be lowered in the sagittal plane well below **45°** (or Lundberg's **32°)** and rotated further to the medial (or inside) in the horizontal plane (as shown in many published studies on the drop of the main longitudinal arch of the foot as evidenced by the lowered position of the navicular bone).

Furthermore, all the existing studies assume a vertical tibia, whereas at midstance in running the tibia is tilted forwarded about **20°** in dorsiflexion. In addition, the ankle joint itself is angled downward on the medial side in this maximally **20°** dorsiflexed ankle position. Neither of these important factors are included in the above ankle joint coupling studies cited in Endnote[2] or in Rubin.

As if these problems were not enough, there is another that is perhaps the worst of all. Although the average angle of inclination assumed in the Endnote[2] studies was **45°**, the actual range was from almost an angle of **70°** for the highest arched (or cavus) foot to only about **20°** for the lowest arched (or planus) or flat foot.

Can any average with that great a range provide meaningful results for individual runners? At the least, average angles in inclination have to be derived for categories of runners, such as normal runners, pronating runners, and supinating runners. Obviously, the only truly accurate biomechanical approach is by each individual runner.

The huge **50°** range of inclination angles for the subtalar joint strongly suggests that each runner's angle is individually determined by the structural reaction to the effect of shoe heel-induced supination on his or her bones of the ankle joint complex.

Shoe Heels Have Greater Effect on Higher Arch Feet, Less on Lower Arch Feet

The bottom line relative to inclination angles of the subtalar joint in the sagittal plane is as follows. Individuals having supinated feet with higher longitudinal arches have inclination angles that are greater than **45°** have more tibial rotation for each degree of pronation or supination during running. Individuals having pronated feet with lower arches have inclination angles that are less than **45°** have less tibial rotation for each degree of pronation or supination. (This was noted by Benno **Nigg** et al. (1993). Effects of arch height of the foot on angular motion of the lower extremities in running. In the ***Journal of Biomechanics*** 26: 8: pages 909-916.)

This is an unusually critical point. It means that shoe heels will generally have a greater effect on individuals having supinated feet with high arches. For example, their tibias will be externally rotated farther during running, increasing the abnormal rotary structure of the modern knee shown in **FIGURE 3.8**.

In contrast, shoe heels will typically have a lessor effect on individuals having pronated feet with low arches, and their tibia will be externally rotated less during running, so that their knees have a more natural, less non-rotary structure that is more like Figure 9B.

The change in the inclination angle is due to a physical change in the position of the subtalar joint (between the ground-contacting calcaneus base and the pivoting talus). Higher arched individuals with supinated feet have a calcaneus that is higher and rotated laterally, while lower arched individuals with pronated feet have a calcaneus that is lower and rotated medially.

The Classical Physics Approach Has Been Lost In the Technical Complexity

The classic physics of Galileo and Newton was built by conducting the simplest experiments possible to test the effects of gravity alone, so as to build a foundation for a general gravitational theory. Secondary factors like air friction are added in later to get results that match the real world.

Following this approach, Galileo used an inclined plane to study gravity without air resistance and with reduced speed to make accurate measurement possible of the acceleration caused by gravity. Newton observed a falling apple from a tree as a simple model of the gravitational force of attraction between planets.

In contrast, the existing basic biomechanics approach to the decoupling anomaly is as if the Galileo and Newton had tried to understand gravity by first studying the actual flight of cannon balls. If they had chosen to do so, gravity might still be a mystery today.

If biomechanics as a science were instead to follow the classic approach, an accurate ankle joint coupling ratio derived from living subjects while stationary is the simple case that would than form a good theoretical baseline, against which actual running results should be measured. The difference with the real world running results must be explained in explicit terms of how and why a ratio derived from stationary living test subjects is altered.

In contrast, without an accurate known baseline to measure against, all test results are just a confusing jumble of data noise, as has been the case heretofore in the study of human ankle joint decoupling.

So, so meaningful running research would logically involve human joint motion in the form of running, which is natural, as one principal difference from a baseline living stationary study. The other principal difference is shoes, which are artificial (and have increasingly major structural effects over time, a hugely complicating issue).

Both differences have to be evaluated with very careful empirical studies against the newly created known baseline, if a classical physics approach is to be followed in order to achieve success in obtaining meaningful results.

Dr. Frederick's Other Major Misgiving About Heel Height Studies Like Mine

Besides his concern on ankle joint decoupling discussed above, Ned also noted in his comments on my book draft that there is not a standardized footwear measurement for the height of the shoe heel above the shoe forefoot, and no generally accepted measurement protocol.

It is certainly true that there is no consistency whatsoever relative to measurement of heel height in the industry (both last and footwear makers) or in the scientific studies of its footwear products, and that is a serious problem that needs resolution. Hopefully, my book will provide a powerful and long-needed impetus for real progress finally in that effort by the industry.

However, it remains unquestionably true today that it is an extremely simple matter to statically measure the essential structural difference in any footwear between the heel area and the forefoot area in a gross but highly meaningful way, even if less than perfectly consistent.

That is currently being done routinely, despite the needless confusion that results when we call the resulting measurement values “heel lift,” “heel offset,” “heel drop,” or “pitch,” “gradient,” or “stack” (all terms commonly used today). Clearly, comparing heel heights can be hard and confusing, but still highly meaningful.

But Dr. Frederick also takes the surprising position that heel height must be dynamically measured during running at instants of maximum deformation in order for there to be any meaningful research results. To say the least, this would be difficult to do accurately, if not practically impossible today.

As noted first above, requiring this challenging approach seems like trying to discover the basic properties of gravity by first studying cannonballs in flight, instead of taking the far simpler initial approaches of Galileo and Newton of reducing a problem to its simplest principal factors. Static measures of heel height are without doubt good enough for meaningful biomechanical test results.

Moreover, it is unclear how dynamic measurement of heel height would be used. What is its purpose? Why do we need it? I frankly have no idea. What exactly is the potential benefit compared to static measurement? More practically, what is the cost versus benefit. Dr. Frederick is silent on all these issues and cites no references upon which his analysis might be based.

And, for closest comparison I can think of, although the side-to-side frontal plane deformation of footwear soles would seem to be at least equally relevant in the important study of running pronation and supination, no such equivalent capability currently exists to study dynamic lateral/medial compression of footwear soles.

Nonetheless, despite that absence, there are a very large volume of existing biomechanical studies that profess to provide meaningful results concerning pronation and supination. Unanswered is the question of why it is not important to measure shoe soles dynamically in the frontal plane during running to study pronation and supination, but critically important in the sagittal plane for heel height?

“Form Follows Function” is Largely Ignored in Running Biomechanics Research

More to the point, unanswered is the question of why it is also not important to at least measure shoe shoes statically in the frontal plane prior to studying pronation and supination during running. Footwear sole structures vary widely in thickness, density, width, and shape in the frontal plane, and they typically vary from one frontal plane section to another, and do so many times throughout the length of the sole. Yet these variations are almost never accounted for in any way in virtually any study, and never in rigorous detail.

Simply put, the structure of footwear soles is a critical but unknown and totally random variable in running biomechanics research, even in its simplest and easiest statically measured form. Does that mean that all such existing running biomechanics studies are sufficiently incomplete as to be generally incapable of producing reliable conclusions?

“Form follows function” is a truism in functional design, but the actual form – this is, structure – is usually ignored in running biomechanics studies. The majority of such studies do not even mention the specific shoe model or models used in the study. None spell out the actual structure of the shoe soles, which are the physical structure directly supporting the running foot being studied.

An Unusually Large Sample Size, But Highly Selected Instead of Random

Finally, getting back to the outstanding Willwacher study discussed at the beginning of this endnote, one of its virtues is that its sample size is much larger than a typical biomechanics study, and includes both men and women. However, unfortunately it must also be pointed out that the runners studied are middle-aged, so on a de facto basis they are highly selected biomechanically, since they apparently have remained runners after surviving many years of annual injury rates as high as 70%.

Moreover, the study’s runners were also limited to those runners who had been injury-free for at least the past 6 months, which makes them very unique indeed, again given the typical 70% annual injury rates.

Therefore, the test subjects were not at all randomly selected and do not at all reflect the overall population, even of their age group. Rather, they are highly filtered, elite winners who have triumphed in a lifelong “survival of the fittest” race in an age group in which nearly all other runners are former runners.

So a truly random study of subjects in this age group would likely including only a small number of active runners to be studied, which of course is why the study and all other running studies are not randomized and therefore do not at all represent the overall population.

This is an extremely serious problem, since it means that there are no existing biomechanical studies on running that examine the effect of shoe heels on the general population. It is expected that in general such effect is far more adverse, with much greater abnormal distortion of joint motion and skeletal structure.

On the positive side, the unique older runners in the Willwacher study above provide a rational guide to interpreting the study results. It is reasonable to conclude that the middle-aged runners’ relatively straight-to-slightly-valgus legs enabled them to avoid injury and continue running far longer that typical.

Given that Willwacher’s data shows that the knee is being torqued into an unnatural varus position, it seems clear that the most effective compensation by runners successful in the long term is moderate pronation that offsets nearly exactly the abnormal torque caused by shoe heels. The same relatively straight-to-slightly-valgus legs is seen generally in world class champions.

However, a quick trip to the mall will convince you that this is not true for the overall population. A large portion of the males are significantly bowlegged when walking, whereas a similar portion of the females are significantly knock-kneed, as discussed in detail earlier.

An important further note: like all running biomechanical studies, the Willwacher study tests and provides results for only one leg, the right, ignoring the other leg on the generally accepted assumption that both legs are the same. However, that convenient assumption has now been definitively proven wrong, because the general case is instead that the right and left legs are in fact asymmetrical in form and function (see Endnote[4] directly below).

Of course, it is easy to understand why most studies have been limited to only one leg: it is extremely difficult to deal with all the data points needed from just one leg to adequately measure its function, let alone both legs, and then correlating the differences between them, while also correlating those leg differences with data points from other parts of the body. As wearable, wireless electronic technology evolves, that complexity problem will become much easier to solve, but historically it has been overwhelming. Not to mention the much higher cost.

A final note: data from the Willwacher study (graph on **Knee Angles in Frontal Plane** – shown above) also provides clear evidence of the extraordinarily high individual range of variation of knee abduction/adduction motion between the 222 runners, as expected given each individual's specific genetic adaptation to their own particular, highly variable shoe heel use.

The frontal plane knee motion shown is also the most erratically variable of all the lower limb joint motions measured in the Willwacher study, suggestive of wide individual variation in compensating for the excessive lateral instability in the modern knee joint due to the unnatural effect of shoe heels.

The Breakdown in Biomedical Research

A section-leading article with the above title appeared recently in ***The Wall Street Journal*** (April 7, 2017). Among many other very troubling studies, it refers to a study titled "Why Most Published Research Findings Are False," (***PLOS Medicine***, August 30, 2005) by John Ioannidis, an epidemiologist and health-policy researcher at Stanford.

The article notes that, unlike drug studies involving humans, "the problem is especially acute in laboratory studies with animals, in which scientists often *just use a few animals and fail to select them randomly*" (italics added). However, that is precisely the main problem with scientific studies on running in shoes: the animals are human Guinea Pigs, just a relative few and not selected randomly from the general population. The vast majority of the general population are non-active runners who are ignored by these studies.

The question of whether many or most of these non-active runners are non-runners due to problems caused by their athletic shoes is neither asked nor answered!

3A. The only direct reference to this matched pair of contradictory of definitions that I have found was by Stephen Messier … & Paul Devita, who clearly state that both definitions are alternatives that mean the same thing, despite being opposites. See **Messier**, Stephen P. … & **Devita**, Paul (2008). Risk Factors and Mechanisms of Knee Injury in Runners. In *Medicine & Science in Sports & Medicine* 1873-1879, especially page 1878.

4. **Radzak**, Kara N. et al. (2017). Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. In ***Gait & Posture*** 51: 268-274, particularly **pages 270-272** and **Tables 2-3**. See also **Lambach**, Rebecca L. (2014). Evidence of Joint Moment Asymmetry in Healthy Populations during Gait. In ***Gait Posture*** 40(4): 526-531. Irene McClay (Davis) in "The Evolution of the Study of the Mechanics of Running" in the ***Journal of the American Podiatric Medical Association*** **90**: 3: 133-148, especially **page 141** and **Figure 8**.

5. Many Research Studies Have Experimentally Confirmed the Twisting Effect of Elevated Shoe Heels on Ankle Joints and Foot

A relatively recent study in 2012 by Danielle **Barkema**, Timothy Derrick, and Philip Martin experimentally confirmed the existence of this artificial supination effect of shoe heels on the ankle joints and foot. Specifically, in an experiment with 15 women, they found that

> **As heel height increased** for both fixed and preferred [walking] speeds, rearfoot angle became more positive throughout stance, i.e. the center of the ankle joint shifted laterally relative to the heel point of contact, which contributes to **an inversion-biased ankle orientation** (Fig. 4).

See **Barkema**, Danielle D. et al. (2012). Heel height affects lower extremity frontal plane joint moments during walking. In ***Gait & Posture*** 35: 483-488, particularly pages 483, 485-487 with Figures 2 & 4. See also Cronin, Neil J. (2014). The effects of high heeled shoes on female gait: A Review. In the ***Journal of Electromyography and Kinesiology*** 24: 258-263. particularly pages 258 and 261.

Another walking study, also in 2012, by Alicia **Foster**, Mark Blanchette, Yi-Chen Chou, and Christopher Powers indicated an increase from low heels (1.3 cm or ½ inch) to high heels (9.5 cm or 3½ inches) coincides with a peak ankle inversion angle increase from 3 degrees to 9 degrees. The high heels take the foot to near maximum supination, since less than 8 degrees has been reported to be about the maximum passive range of motion for inversion.

See **Foster**, Alicia et al. (2012). The Influence of Heel Height on Frontal Plane Ankle Biomechanics: Implications for Lateral Ankle Sprains. In ***Foot & Ankle International*** 33: 64-69, particularly pages 64, **67 with Table 1** and **Figure 3B**, and 68.

In an earlier study with 37 women in 2000, Makiko **Kouchi** and Emiko Tsutsumi also found that as the height of a shoe heel increases, the foot supinates, as did a study with 13 women in the same year by Darren **Stefanyshyn** and others.

See **Kouchi**, Makiko & Tsutsumi, Emiko (2000). 3D Foot Shape and Shoe Heel Height. In ***Anthropological Science*** 108: 4: 331-343, particularly page **331**, 336-338 with **Figures 5-7**, and **342**. **Stefanyshyn** et al. (2000), The Influence of High Heeled Shoes on Kinematics, Kinetics, and Muscle EMG of Normal Female Gait. In the ***Journal of Applied Biomechanics*** 16: 309-319, particularly pages 309, 313-316. See also **Hong**, Wei-Hsien et al. (2013). Effect of Shoe Heel Height and Total-Contact Insert on Muscle Loading and Foot Stability While Walking. In ***Foot & Ankle International*** 34: 2: 273-281, particularly pages **273**-274, 276-**277** with **Figure 3(b**), and 279 with Figure 5.

In addition, a study in 2002 by Timothy **Derrick**, Darrin Dereu, and Scott McLean indicated that foot becomes more inverted at impact at the end of an exhaustive run in conventional running shoes, demonstrating a direct cause and increasing effect, even in a relatively short period of time.

See **Derrick**, Timothy R. et al. (2002). Impacts and kinematic adjustments during an exhaustive run. In ***Medicine and Science in Sports and*** *Medicine* 998-1002, particularly pages **998** and 1000-**1001 with Table 2**. See also **Clarke,** T. E. et al. (1983). The effects of shoe design parameters on rearfoot control in running. In ***Medicine and Science in Sports and Exercise*** 15: 5: 376-381, particularly page **377 with Fig. 1**.

6. **Derrick**, Timothy (2004). The Effects of Knee Contact Angle on Impact Forces and Accelerations. In *Medicine & Science in Sports & Exercise* 832-837, especially **Figure 6 on page 836**. **Kerrigan**, Casey D. (2009). The Effect of Running Shoes on Lower Extremity Joint Torques. In *Physical Medicine and Rehabilitation* 1:12: 1058-1063, particularly pages **1058** and **1060** with **Figure 1**. **Messier**, Stephen P. et al. (2008). Risk Factors and Mechanisms of Knee Injury in Runners. In *Medicine & Science in Sport & Exercise* 1873-1879, particularly page **1877-8**. See also **Novacheck**, T. F. (1998). In *Gait & Posture* 7: 77-98, especially pages 81-**82** with **Figures** 5-**6, 90-91**with **Figure 16** .

7. **Sunnegardh**, J. et al. (1988). Isometric and isokinetic muscle strength, anthropometry and physical activity in 8 and 13 year old Swedish children. In the *European Journal of Applied Physiology* 58: 291-297, especially pages **291** and **295-296 & Figure 1**.

8. **Altman**, Morton I. (1968). Sagittal Plane Angles of the Talus and Calsaneus in the Developing Foot. In the *Journal of the American Podiatry Association* 58: 11: 463-470, especially pages **466-469** and **Figures 2-6**. In *A Compendium of Podiatric Biomechanics*, Sgarlato, Thomas E. (Ed.). San Francisco: California College of Podiatric Medicine (1971),

pages 191-198.

9. **Fregly**, Benjamin et al. (2012). Grand Challenge to Predict In Vivo Knee Loads. In the *Journal of Orthopaedic Research* April 503-513, especially page **505**.

10. **du Toit**, Guilluame (1955). Internal Derangement of the Knee. In *Instruction Course Lectures* (R. Beverly Raney, ed.). Vol. XII: 9-34, particularly pages **15-17**.

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13. **PBS NOVA** (2014) "Roman Catacomb Mystery." It is important to note here that the proceeding photographic samples in Figures 3.4-3.5 were not cherry-picked from many other possible choices. They are simply the only ones I could find after an extensive search of available studies ranging over the last century and a half. Hopefully this book will prompt field studies conducted at the various locations all over the world where that are many ancient bones potentially available for study by professional anatomists and physical anthropology. The only contrary evidence I found was a drawing (Figure. 25 on page 177) of a Neolithic tibia in John Cameron (1934) *The Skeleton of British Neolithic Man*. London: Williams & Norgate Ltd. It shows elongation of the medial surface of the tibia, but no evidence of rotation.

14. See **Selected Knee Osteoarthritis References** below, after the last Endnote for Chapter 3

15. See for example **Kerrigan**, D. Casey et al. (1998). Women's shoes and knee osteoarthritis. In *The Lancet* 357, April 7, 1097-1098, particularly **both pages**, and **Kerrigan**, D. Casey et al. (1998). Knee osteoarthritis and high-heeled shoes. In *The Lancet* 351, May 9, 1399-1401, particularly pages **1399** and **1401**. Again, see Endnote 13 below.

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Chapter 11. A MAJOR MISALIGNMENT: BOTH FEET AND BOTH LEGS TILTED OUTWARD, ROTATING THE PELVIS BACKWARDS

Chapter 12. SHOE HEELS TYPICALLY MAKE BOYS BOW-LEGGED

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Chapter 16. SHOE HEELS CAUSE THE CROSSOVER OF FEET

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> ...Because the rearfoot and the knee are mechanically linked by the tibia …, eversion in the foot normally leads to internal rotation at the knee. However, in our study eversion and abduction at the rearfoot was increased in the injury group but the internal rotation at the knee was not increased.
>
> ...The third characteristic identified in subjects with subsequent was an accelerated re-inversion with a more lateral roll-off.

This study shows how the elevated shoe heel-induced mechanism whereby foot supination forces the tibia to rotate externally and that external rotation of the knee is locked in throughout the time the abnormally tilted out leg is forcing an unnaturally excessive degree of pronation and pain in barefoot runners. And, more importantly, how this unnatural shoe heel-induced mechanism is locked into the body structure and function of barefoot runners even without the mechanism causing shoes on. So this study shows that running barefoot does not solve the shoe heel-induced problem, which is baked in over time.

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