History and Evolution of Foot and Lower Extremity Biomechanics and Foot Orthoses

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Biomechanics and foot orthoses have evolved over the centuries
Many talented individuals have increased our knowledge in foot and lower extremity biomechanics and about foot orthoses
What people and events have shaped history and evolution of podiatric biomechanics and orthoses?

Aristotle
Aristotle (384-322 BC), Greek scientist and philosopher, was one of earliest biomechanics authors
His treatise, *About the Movement of Animals* (350 BC) provided first scientific analysis of gait and first geometric analysis of muscular actions on bones
First accurately described GRF as: “…for just as the pusher pushes, so the pusher is pushed”

Archimedes
Archimedes (287-212 BC)
was Greek scientist who is considered one of greatest mathematicians of antiquity
Discovered principles of hydrostatics, statics and physics of levers, working to solve the problem of moving a given weight by a given force
"Give me a place to stand on, and I will move the Earth"

Galen
Galen (129-201 AD) was Roman physician and surgeon
Considered first “sports physician”
Was “team doctor” to Roman gladiators by age 28
In his work *De Motu Musculorum* (On the Motion of Muscles), he first explained difference between motor and sensory nerves and agonist and antagonist muscles
Sought to raise medicine to level of exact science

Leonardo DaVinci
Leonardo DaVinci (1452-1519), Italian painter, sculptor and inventor, had keen interest in form & function of human body
Inspired by desire to accurately represent human movement in his paintings and sculptures
In regard to running form on varied surfaces, DaVinci wrote:
“He who runs down a slope has his axis on his heels; and he who runs uphill has it on the toes of his feet; and a man running on level ground has it first on his heels and then on the toes of his feet.”
Giovanni Borelli
- Giovanni Borelli (1608-1679), Italian physicist, physiologist, and mathematician, wrote first book on biomechanics, De Motu Animalium, in 1685
- First to fully describe geometrical principles of levers of musculoskeletal system and that muscles produce much larger forces than resisting external forces
- Borelli found forces required for equilibrium in various joints of human body before Newton
- Borelli is often called: “Father of Biomechanics”

Isaac Newton
- Isaac Newton (1642-1727), British mathematician and physicist, is considered by many to be greatest scientist of all time
- Invented calculus at age 24
- Published Philosophiae Naturalis Principia Mathematica in 1686 which contained his now famous Three Laws of Motion
- Credited with creating the laws of inertia, acceleration, action and reaction forces and of gravity

Nicolas Andry
- Nicolas Andry (1658-1742), a French physician, first coined the term “orthopedics” meaning “straight child”
- Published book, Orthopaedia: The Art of Correcting and Preventing Deformities in Children in 1740
- “If the feet incline too much to one side, you must give the child shoes that are higher on that side, both in the sole and heel, which will make him incline to the opposite side.”

Petrus Camper
- Petrus Camper (1722-1789) was a Dutch physician and pioneer in pediatrics
- Published one of first books on foot deformities, “On the Best Form of Shoe” in 1781, which was reprinted into 14 editions
- Camper’s book stimulated interest in placing arch-supporting orthoses into shoes for children’s flat foot

“...It is surprising that while mankind in all ages have bestowed the greatest attention upon the feet of horses, mules, oxen, and other animals of burthen of draught, they have entirely neglected those of their own species, abandoning them to the ignorance of workmen, who, in general, can only make a shoe upon routine principles, and according to the absurdities of fashion, or the depraved taste of the day. Thus, from our earliest infancy, shoes, as at present worn, serve but to deform the toes and cover the feet with corns, which not only render walking painful, but, in some cases, absolutely impossible.” P. Camper, 1781

Lewis Durlacher
- Lewis Durlacher (1792-1864), a British chiropodist, was royal chiropodist appointed to Queen Victoria
- In 1845, he developed leather foot orthosis to correct for “plantar pressure lesions” and “foot imbalances”
- Durlacher first described intermetatarsal neuroma, over 30 years before T.G. Morton
Hugh Owen Thomas

Hugh Owen Thomas (1834-1891) was a British orthopedic surgeon with interest in treating feet.
- In 1874, Thomas suggested using a “few pennies worth of leather” for lifts, bars, and wedges on shoes to treat foot problems.
- Invented, in 1876, “crooking” of shoe heel, to extend the heel under the antero-medial aspect of shoe sole for treating pronated feet (now called “Thomas heel”).

Newton Melman Shaffer

Newton M. Shaffer (1846-1928), a New York City orthopedist, first described high arched foot with multiple clawtoes.
- Became widely known as “Shaffer’s Foot”.
- Also designed a high-medial arched orthosis with a heel cup which became known as a “Shaffer Plate”.

Royal Whitman

Royal Whitman (1857-1946) was a 1882 Harvard Medical School graduate and New York City orthopedic surgeon that had special interest in foot function.
- Wrote numerous textbooks on orthopedic surgery and taught orthopedics for 40 years.

Whitman’s “Weak Foot”

The deformity then may be analyzed as follows: (1) The leg is displaced inward, so that the weight falls upon the inner side of the foot. (2) The leg is rotated inward so that a line drawn through its center, prolonged from the crest of the tibia, instead of falling over the second toe, now points inside the great toe, or even over the center of the internal border of the foot (Figs. 538 and 547). Whitman's description of “weak foot” very closely matches our current description of the pronated, flat-arched foot with an internally rotated tibia.

Whitman’s Three Grades of “Weak Foot”

1st Degree: The normal foot improperly used, as shown by the method of standing and walking.
2nd Degree: The foot in which the range of voluntary motion is restricted, showing disuse of function, and in which the elements of deformity are apparent when weight is borne.
3rd Degree: That in which the passive range of motion is restricted, or in which there are evident weakness and deformity. This limitation of motion depends, as a rule, on accommodative changes in structure to the habitual postures or to the deformity.

Whitman’s Foot Brace

- Developed in 1885.
- Made from plaster cast taken with foot in supinated position.
- 18-20 gauge sheet steel was formed into a high medial arch brace.
- Goal was to raise medial arch so foot would be less pronated.
Percy Willard Roberts

- Percy W. Roberts (1867-1937), American orthopedic surgeon, developed metal foot orthosis in 1912
- Roberts foot orthosis had deep inverted heel cup that attempted to tilt rearfoot into inverted position
- Had medial and lateral clips and narrow heel cup
- Roberts brace applied too much force over too little area and tended to cause irritation to plantar foot

1895 - Beginning of Chiropody

- During most of 19th century, medical doctors showed little interest in treating foot problems
- Barbers, families and practically anyone that showed an interest in treating feet adopted the “craft” of foot care to fill the void in healthcare of the foot that was left by medical doctors
- In 1895, group of dedicated practitioners in New York successfully appealed to NY State Legislature to first establish chiropody (now podiatry) as a licensed profession

First Podiatry Society & School Formed

- In 1895, Pedic Society of New York became first official society for chiropody/podiatry
- First school of chiropody established in New York in 1911
- In 1912, first national podiatry association, and precursor to current APMA, American National Chiropody Association, was formed and is now 100 years old

Podiatric Approach to Foot Biomechanics in Early 20th Century

- Approach to foot mechanics in early 20th century was based largely on shape of medial longitudinal arch with “normal foot” being viewed as having “normally arched architecture” with treatments geared toward restoring a “normal arch”
- Many podiatrists relied on orthopedic shoe makers to make custom leather foot or steel appliances to treat “weak feet”

Otto Frederick Schuster

- Otto F. Schuster (1881-1936) arrived in US in 1906 from Hamburg, Germany where he had trained as a brace maker
- Schuster started making Whitman braces for Royal Whitman and other orthopedists in NY in 1909
- Became a podiatrist in 1911

First Podiatric Orthopedics Text

- Otto F. Schuster became professor of orthopedics at NY Podiatry School
- In 1927, published first podiatric orthopedics text, Foot Orthopedics, later rewritten by his podiatrist-son, Otto N. Schuster
- Foot Orthopedics remained in use as a valuable textbook until 1950s
Roberts-Whitman Brace

- In the 1920s, Otto F. Schuster combined ideas of Roberts brace with Whitman brace to make Roberts-Whitman brace.
- Roberts-Whitman brace had deep inverted heel cup, high medial arch and wider profile that provided better pronation control and allowed for more comfortable medial arch.

Dudley J. Morton

- Dudley Joy Morton (1884-1960) was physician, anatomist and anthropologist.
- Work focused on shortened 1st metatarsal, “hypermobility” of 1st metatarsal segment and correlation of 1st ray mechanics to excessive foot pronation.

Morton Was First to Describe Load-Deformation of 1st Ray in 1935

- "If the plantar ligaments of any segment are slack when the head of its metatarsal bone lies on the same plane as the others whose ligaments are taut, that segment will fail to share in the carriage of body weight..."

Morton’s Compensating Insole

- In 1932, Morton designed a “compensating insole” that focused on elevating first metatarsal head and preventing pronation compensation for short, “hypermobile” first ray.
- Morton also designed in-shoe support with high medial arch-flange to resist pronation.

Morton believed “hypermobility of first metatarsal” affects foot in three ways:

1. Second metatarsal has “increased burden” since first metatarsal “fails to assume” its normal share of weight.
2. Foot pronates because “medial buttress” is ineffective until “slack in its ligaments is taken up” as pronation increases.
3. As pronation advances, “functional stresses are thrown increasingly on muscles on inner side of ankle, imposing them undue strain.”

First Plaster Splint Impression Casting of Foot

Edward Reed, MD, an orthopedic surgeon from Santa Monica, California, was first to describe plaster splint impression casting for foot orthoses in 1933. Reed EN: A simple method for making plaster casts of feet. JBJS, 17:1007, 1933.

Alan Murray & Benjamin Levy

In 1930s, Alan Murray, ice skater, developed shoe molded directly onto cast of foot called the Murray Space Shoe. NY podiatrist, Benjamin Levy, developed idea of using inner sole from Murray Space Shoe as a removable cork and leather insole with a toe crest, became known as Levy mold. Levy B: An appliance to induce toe flexion on weight bearing. J Foot: 1930.

John Tinkham Manter


Manter’s Mean STJ Axis Location in 16 Cadaver Feet


Manter’s Study Determined STJ Axis to Transverse and Sagittal Planes

Manter’s 1941 study found that mean position of STJ axis in 16 cadaver feet was angulated 16° from sagittal plane and 42° from transverse plane. Manter’s study only determined angular deviation of STJ axis from cardinal planes, but did not determine spatial location of STJ axis in relation to plantar foot (i.e. whether STJ axis was medially or laterally positioned). Manter JT: Movements of the subtalar and transverse tarsal joints. Anat Rec, 80:397-410, 1941.
Manter’s Midtarsal Joint Axes

- Longitudinal transverse tarsal joint axis
  - 9° from transverse plane
  - 15° from sagittal plane
- Oblique transverse tarsal joint axis
  - 52° from transverse plane
  - 57° from sagittal plane

Oblique transverse tarsal joint axis
- 52° from transverse plane
- 57° from sagittal plane

John H. Hicks

- John H. Hicks (1915-1992), orthopedic surgeon from Birmingham, UK, had great interest in foot biomechanics and performed pioneering research
- Wrote series of classic scientific papers from 1953-1961 on biomechanics of foot, plantar fascial function and biomechanics of balance relative to GRF
- Also determined axes of motion of ankle joint, STJ, MTJ, first ray and fifth ray

Manter's Midtarsal Joint Axes

- Oblique midtarsal joint (OMTJ) axis
- Antero-posterior midtarsal joint (APMTJ) axis

However, Hicks’ MTJ axes were in different locations to Manter’s MTJ axes


Hicks’ Midtarsal Joint Axes

- In 1953, Hicks found two distinct MTJ axes
  - Oblique midtarsal joint (OMTJ) axis
  - Antero-posterior midtarsal joint (APMTJ) axis
- However, Hicks’ MTJ axes were in different locations to Manter’s MTJ axes


Windlass and Reverse Windlass Effect

- Hicks also noted that body weight flattened arch and plantarflexed hallux more forcefully into ground
- Effect of hallux forcefully pressing into ground was noted to nearly disappear with transection of plantar fascia in cadaver foot


Hicks was first to describe the “Windlass Effect” of hallux dorsiflexion in 1954


Hallux dorsiflexion in cadavers and live subjects produced following simultaneous responses:
- Increase in medial longitudinal arch height
- Inversion of rearfoot
- External rotation of leg
- Appearance of tight band in region of plantar aponeurosis


Herbert Oliver Elftman

- Herbert O. Elftman, PhD, professor of anatomy at Columbia University, wrote many papers on foot and lower extremity biomechanics from 1934 to 1970
- Elftman proposed that MTJ has joint axes and motion that may be affected by subtalar joint pronation and supination

Elftman thought that in the pronated foot major axis of TNJ (TN-1) was directly in line with CC-1:
"allows the forepart of the foot to move freely with respect to hindpart without movement of the talus with respect to the calcaneus"
Thought that MTJ axis changes in location as STJ rotates from pronated to supinated position:
"In passing from pronated to supinated position there is a continuous change in positions of significant joint elements and, consequently, of instantaneous transverse tarsal axis."

Verne Thompson Inman
- Verne T. Inman, MD, PhD (1905-1980) began to research lower extremity biomechanics in 1957 at UC Berkeley due to need for better prostheses in post-WW II amputees
- His two books: *The Joints of the Ankle and Human Walking* are classics in foot and lower extremity biomechanics

Howard Davis Eberhart
- Howard D. Eberhart was professor in civil engineering at UC Berkeley, when accident required BK amputation
- Verne Inman, professor of orthopedic surgery at UC Berkeley, was surgeon that amputated Eberhart's leg in 1944
- In order to research lower limb biomechanics and develop better prosthesis designs, Eberhart teamed with Inman and became director of Prosthetics Devices Research Project at UC Berkeley Dept. of Engineering

UC Biomechanics
- UCBL was center of research in foot and lower extremity biomechanics and prosthetics research from 1957 to 1974 at UCSF and UC Berkeley
- During its time, UCBL produced more research and notable researchers in foot and lower extremity biomechanics than any other in world

D. Gilbert Wright
- Researcher at UC Biomechanics Lab who, in 1964, performed classic studies of range of motion of STJ during walking and on elastic properties of plantar fascia

John B. Saunders
- Chairman of Dept of Anatomy at UC Berkeley from 1938-1956
- Coauthored classic article on determinants of gait, described how locomotion mechanisms minimize excursion of CoM during gait

John B. Saunders (1903-1991)

In 1969, dental student, R.E. Isman, did study with Verne Inman at UC Biomechanics Lab that measured STJ axis in 46 cadaver feet. STJ was 42° inclined from transverse plane and 23° adducted from sagittal plane. Isman RE, Inman VT: Anthropometric studies of the human foot and ankle. Bull Pros Research, 10:97-129, 1969.


UCBL orthosis primarily used by orthopedic community for treatment of pediatric flexible flatfoot deformity.

Henderson & Campbell: UCBL

Merton Louis Root

Merton L. Root (1922-2002) became interested in research as a WW II army paratrooper. After war decided to pursue career in podiatry in 1948 after seeing need for better research in podiatry. Graduated from California College of Chiropody in 1952. Started world’s first Department of Podiatric Biomechanics in 1966 at CCPM in San Francisco.

San Francisco Bay Area became hub for foot and lower extremity biomechanics research and development in late 1950s and 1960s.

Merton Louis Root

Root’s Eight Biophysical Criteria for “Normalcy”


Root, et al proposed that all feet and lower extremities which did not meet criteria for “normal” had structural defects and were, therefore, “abnormal.”

Root’s “Deformities” Based on STJ Neutral

Root developed biomechanical classification system based on concept that STJ neutral was ideal foot position during gait. Root classified “foot types” with frontal plane positions of rearfoot to tibia, forefoot to rearfoot, and first ray position relative to 1st - 5th metatarsal.
Root Developed “Neutral Suspension Casting Method”

- In 1971, Root, Weed and Orien described “neutral suspension casting technique” with plaster splints to accomplish the following objectives:
  - Capture STJ in neutral position
  - Dorsiflex the 4th and 5th metatarsals
  - Pronate midtarsal joint to maximum to “lock” forefoot against rearfoot
  - Preserve NWB plantar contour of foot


Root Functional Orthosis

- Root was one of first to experiment with new materials called thermoplastics and began to develop his Root Functional Orthosis in 1958
- RFO had lower MLA than previous orthoses since Root didn’t believe that high MLA or arch pain was necessary to control abnormal pronation
- Root designed his RFO to allow the STJ to function in neutral position by preventing “compensation” for rearfoot and forefoot “deformities”

Root’s Lectures Notes Published by Sgarlato

- Thomas E. Sgarlato, DPM, took over as chairman of world’s first Department of Podiatric Biomechanics from Root (due to illness) in 1969
- Sgarlato worked with podiatry students and biomechanics faculty to publish Root’s lecture notes as “A Compendium of Podiatric Biomechanics” in March 1971

E.J. Van Langelaan

- E.J. Van Langelaan, orthopedic surgeon in Netherlands, did first modern study on motions of STJ and MTJ in 1983 in his landmark PhD thesis using 3D xray photogrammetry
- Performed under guidance of Antony Huson, PhD at University of Leiden, Netherlands


Apparatus Used in Van Langelaan Study

(Videos courtesy of A. Huson, MD, PhD)
Thoughts from Van Langelaan

- "...intertarsal joints are not 'complicatedly structured but functionally simple hinge joints'. Movements are found to take place around an axis which moves continuously, and the position of which could be approximated with the aid of a bundle of discrete helical axes."
- "The relative axes within a bundle proved to approach each other more closely at characteristic sites in the tarsus." TNJ: central portion of talar head, CCJ: dorsal-medial-superior corner of CCJ

Benno M. Nigg

- Benno Nigg, trained as nuclear physicist, became interested in biomechanics in 1971
- Founded and developed world's largest biomechanics research facility at University of Calgary in 1981
- Has authored/editor ed 10 books and has authored over 290 scientific papers on sports shoes and foot and lower extremity biomechanics

Howard J. Dananberg

- Howard Dananberg popularized concept that functional hallux limitus was key to abnormal foot function
- FnHL thought to produce "sagittal plane blockade" during walking that caused pronation of foot as result
- Patented "kinetic wedge" to address his theory of "sagittal plane blockade"

Richard L. Blake

- Richard Blake, a 1981 CCPM Biomechanics Fellowship graduate, developed the Blake Inverted Orthosis from 1981-1982

Blake Inverted Orthosis

- As Dr. Blake developed his BIO, he discovered that increasing levels of cast inversion increased pronation control from his inverted orthosis due to increased MLA height and inverted heel cup
- However, as cast inversion approached 10°, Dr. Blake noted new orthosis problems:
  - Plantar fascial irritation
  - Foot slid laterally off of orthosis plate
  - Excessive orthosis arch height caused late midstance pronation, instead of late midstance supination, during walking

Blake Inverted Orthosis

- Positive cast of BIO inverted 15, 25 or 35° which causes varus heel cup and higher medial arch to orthosis
- Modified medial arch fill and planter fascial accommodation are added to prevent plantar fascial irritation
- Heel cups of 20 mm and flat rearfoot posts are standard
New Research on STJ Axis Location Emphasized STJ Kinetics

In 1987, concept that STJ axis location may be determined clinically and that GRF medial to STJ axis causes supination moments and GRF lateral to axis causes STJ pronation moments was first introduced.


In 1989, concept of rotational equilibrium used to explain how balance of STJ moments may explain abnormal internal forces within foot and different types of foot pathology.


In 1992, medial heel skive technique, was first described as method to increase varus shape of heel cup in functional foot orthosis.

Designed to increase STJ supination moment from orthosis and more effectively treat symptoms caused by excessive pronation moments such as PTTD and children’s flatfoot deformity.


SALRE Theory Explains How Orthoses Alter STJ Moments

If orthosis is designed to “control pronation”, ORF will be shifted medially so STJ supination moment is increased.

If orthosis is designed to “control STJ supination”, then ORF will be shifted laterally so STJ pronation moment is increased.


As STJ axis becomes medially deviated, orthosis has decreased area medial to STJ axis to cause STJ supination moments.

Medial deviation of STJ decreases orthosis ability to supinate STJ.
Tissue Stress Model

- Tissue stress model first proposed as a model for mechanical foot therapy in 1995 by McPoil and Hunt
- Tissue stress model is not a novel idea since it is based on same ideas already in current use in treatment of parts of body other than foot and lower extremity
- Tissue stress model doesn’t rely on “unreliable measurement techniques”

Tissue Stress Allows Efficient Determination of Orthosis Goals

- Orthosis goals are best achieved by specifically designing CFO to:
  - reduce stress on injured structural components within foot and lower extremity
  - optimize function of foot and lower extremity for specific weightbearing activities
  - prevent other injuries or pathologies from occurring due to foot orthosis therapy

Steps to Using Tissue Stress

1. Specifically identify anatomical structures which are source of patient’s complaints
2. Determine structural and/or functional variables which may be source of pathological forces on injured structures
3. Design orthosis/shoe treatment plan which will most effectively reduce pathological forces on injured structural components, will optimize gait function and will not cause other pathology or symptoms

Paul Robert Scherer

- Paul Scherer, DPM, is former professor of biomechanics at CCPM and current professor of biomechanics at CSPM
- Scientific chair for first ten PFOLA Conferences which were world-class international events that presented latest knowledge in biomechanics and foot orthosis therapy
- His book “Recent Advances in Orthotic Therapy” is premier educational resource detailing scientific research evidence for orthosis therapy

Benno Nigg’s Preferred Movement Pathway Model

- In 2001, Benno Nigg proposed “preferred movement pathway model” of orthosis function
- Nigg proposes that orthoses do not function by realigning skeleton but rather alter input signals into plantar foot that change “muscle tuning”
- Nigg proposed that if foot orthosis counteracts preferred movement path, then muscle activity will increase and that optimal shoe or foot orthosis design will reduce or minimize muscle activity

Chris Nester

- Chris Nester, first a podiatrist then a PhD in biomechanics, became foot biomechanics researcher at University of Salford, UK.
- Along with coworkers, Nester has performed important pioneering bone pin research in kinematics of foot joints in both cadaver and live feet.

Nester and coworkers were first to suggest that previous model of simultaneously occurring oblique and longitudinal MTJ axes can not occur and should be replaced by a single moving MTJ axis.

Simple concept described by Nester et al is very important for understanding MTJ biomechanics: "axes of rotation do not determine the motion at a joint; rather, the motion determines the axis"  

Important Coworkers Have Further Developed STJ Theory

- Also proposed three “reference axes” for MTJ:
  - Medial-lateral MTJ axis (z-axis)
  - Anterior-posterior MTJ axis (x-axis)
  - Vertical MTJ axis (y-axis)


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Future for Foot and Lower Extremity Biomechanics and Orthoses?

- Key to developing better understanding of gait function and pathologies will be dependent on research that determines forces and moments acting on foot and lower extremity.
- Research into new orthosis designs to reduce abnormal forces and moments causing certain pathologies will be important for further progress.
- Better understanding of biological and mechanical nature of human tissues will also be critical to developing better treatment methods.
Biomechanics and Historical Sources

- W. Eric Lee: Podiatric Historian from UK
  Lee WE, Martin L. Root: An appreciation. The Podiatric Biomechanics Group

- Richard O. Schuster: Podiatrist from US
  (nephew of Otto N. Schuster)

- Benno Nigg: Biomechanics Researcher
  Nigg BM. “Selected historical highlights”, in Biomechanics of the Musculo-Skeletal System, 2nd Edition

Conclusion

- History demonstrates that foot and lower extremity biomechanics theory and foot orthosis treatments
  have all evolved over time
- Many individuals have made contributions towards better understanding of lower extremity function
  and treating foot and lower extremity mechanical pathologies with orthoses
- Examples of those that changed history in foot-health professions show that advances in knowledge
  require sacrifice, determination and hard work