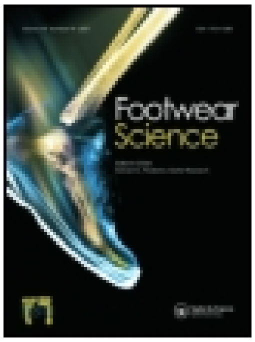

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Biomechanical considerations on barefoot movement and barefoot shoe concepts

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Biomechanical considerations on barefoot movement and barefoot shoe concepts

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The purpose of this paper is to discuss biomechanical considerations related to 'barefoot running' and 'barefoot shoes'. Biomechanical differences include increases in external force loading rate, higher tibial acceleration, flatter foot placement, higher ankle joint stiffness and earlier EMG intensity for the tibialis anterior. There is indirect evidence that barefoot training strengthens small and large muscles crossing the ankle joint. Furthermore, there is evidence that barefoot running has energetic advantages over shod running. There is, however, no evidence that barefoot running would have more or less injuries than shod running. 'Barefoot shoes' include (a) the 'Feet You Wear' concept where the shape of the foot is mimicked, (b) the Nike Free concept where the kinematics of barefoot running are mimicked, and (c) the MBT (Masai Barefoot Technology) concept where the feeling of barefoot walking and/or running is mimicked. These shoes are based on very different conceptual ideas. However, all of them seem to provide a benefit to the athlete, independent on whether they are based on copying the shape of the human foot, the movement during barefoot running or the feeling of barefoot movement on soft ground. The name 'barefoot shoes' is a contradiction in terms. A shoe condition is not a barefoot condition. The discussed 'barefoot shoes' typically take one aspect of barefoot and implement it into a shoe. To assume that these shoes correspond to barefoot running or moving is not appropriate and the name 'barefoot shoes' may well be more a marketing strategy than a functional name.

Keywords: ankle joint; barefoot; Barefoot running; EMG; injuries; muscle; running; shoes

At the 1960 Olympic Games in Rome, Abele Bikila won the Marathon with a new world record time of 2:15:16. He was added to the Ethiopian Olympic team only as a last minute replacement. The interesting aspect of Abebe Bikila's victory was that he ran barefoot. Four years later, at the 1964 Olympic Games in Tokyo, he entered the marathon again, this time running in a pair of Onitsuka Tiger shoes, a sub-brand of ASICS today. He won the Olympic Marathon again with a new world record time of 2:12:11.

Zola Budd, born in 1966 in South Africa broke the world record in the women's 5000 m twice, the first time at the age of 17 with a time of 15:01:83, a record that was not accepted by the IAAF due to political reasons. However, she broke the world record a second time 2 years later with a time of 14:48.07. The interesting aspect of Zola Budd's performance was that she always trained and competed barefoot.

These exceptional performances open basic questions around the topic of 'barefoot running' and barefoot movement in general such as

(1) What are the biomechanical differences between barefoot and shod running?
(2) What are the training effects of barefoot running?
(3) What are the performance/economy advantages of barefoot running?
(4) Is there an association between barefoot/shod running and injuries?

Barefoot and shod running, biomechanical differences

Differences in kinematics, kinetics and muscle activity have been described frequently in the literature. Selected results can be summarized as:

- Increase of the external vertical loading rate for barefoot compared to shod running (de Wit *et al*. 2000).
- Earlier impact peak for barefoot compared to shod running (de Wit *et al*. 2000).
- Higher tibial acceleration for barefoot than for shod running (McNair and Marshall 1994).
- Flatter foot placement at initial contact for barefoot compared to shod running (Herzog 1978, de Wit *et al*. 2000, Bishop *et al*. 2006).

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- Larger minimal knee angle for barefoot compared to shod running (de Wit and de Clercq 2000).
- Small and unsystematic differences in foot eversion and tibial rotation between barefoot and shod running when using bone pin measurements (Stacoff *et al.* 2000).
- Higher ankle joint stiffness and lower knee joint stiffness for barefoot compared to shod running (Coyles *et al.* 2001).
- Earlier maximal EMG intensity for tibialis anterior for barefoot compared to shod running (von Tscharner *et al.* 2003).

Barefoot and training effects

Barefoot training has been used by coaches for a long time with the suggestion that barefoot training improves the strength of the overall muscular system and that barefoot training trains all the muscles, including both the large muscles like the biceps femoris and the gastrocnemius, as well as small muscles like the soleus and the peroneus longus. It has been suggested in coaching circles that a well balanced development of all muscles crossing a joint is essential for performance and for injury prevention.

Indirect experimental evidence for the importance of the training of small muscles was provided through a study quantifying the injury frequency of adolescents with and without wobble board training (Emery *et al.* 2005). The results of this study showed that the adolescent test subjects exposed to wobble board training showed less sport related injuries than the test subjects who were not exposed to this training. It was speculated that the wobble board training strengthened the small and large muscles and provided a more all around muscle development especially for muscles crossing the ankle joint, where many small muscles could be involved in motion and motion control. The relationship between wobble board training and barefoot training is that both training forms strengthen the small and large muscles crossing the ankle joint.

Some large muscles may have lines of action that are not optimal for sensing changes in specific directions. In the ankle joint complex, for instance, the triceps surae and the tibialis anterior are 'large' muscle groups. They are ideal for sensing changes in movement for flexion-extension but not well suited for sensing changes for foot ab-adduction and in-eversion. The triceps surae, for instance, would sense changes in in-eversion late and would have to apply extensive forces to readjust the ankle joint position because the movement would have already made progress. For many changes in position, there are small muscles that can provide joint stability quickly and with little force, and although one does not voluntarily select specific muscles to stabilize a joint, it is the training of these smaller and 'quicker' muscles that can increase the general stability of a joint. The effect of strong small muscles has been simulated with a mechanical model using small and large springs (Nigg 2005). The model calculations assumed four strong long springs with large levers with a defined reaction time T_1 (Figure 1 left). For the situation representing strong small muscles, the model calculations assumed again four strong long springs with large levers with the same reaction time, T_1, and additionally four smaller springs with a smaller lever and with a reaction time T_2 (Figure 1, right) with $T_2 = \frac{1}{2} T_1$. This assumption was

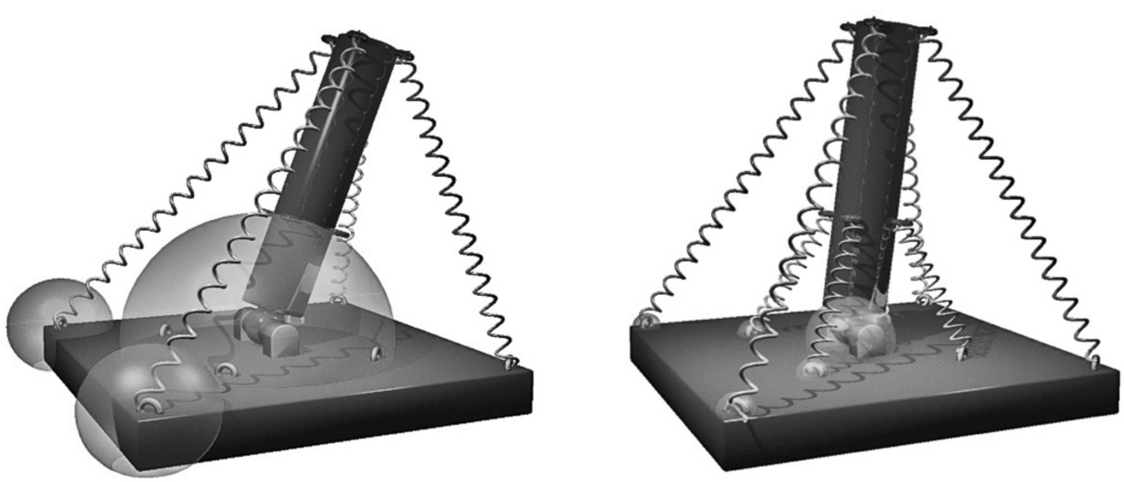

Figure 1. Effect of strong and weak small springs (muscles) on forces in the joint and in the attachment locations of the springs (insertion forces). The simulations were made assuming that the small springs react faster than the large springs. (From Nigg, 2005 with permission of the author.).

made because, as mentioned, some small muscles crossing the ankle joint react faster to changes in joint position. The model calculations showed that the forces in the joint and the insertions were substantially lower for the condition with the strong small springs (Figure 1).

These model calculations support the idea that strong small muscles may be an advantage for performance and protection. Consequently, barefoot training or related strategies strengthening the small muscles crossing the ankle joint would be beneficial for the athlete.

Barefoot and performance

The total work during a physical activity can be quantified using oxygen consumption measurements during the task of interest (Cavanagh and Williams 1982, Fukuda *et al.* 1983). Oxygen consumption for running barefoot and running with running shoes shows typically a difference of about 4 to 5% in favour for running barefoot (e.g. Flaherty 1994). This finding is at first glance surprising and the magnitude of the reported difference is substantial.

The increase in oxygen consumption with running shoes may be due to various factors. Possible reasons include (Webb *et al.* 1988, Nigg *et al.* 2000, Stefanyshyn and Nigg 2000, Warburton 2001)

- the acceleration and deceleration of the additional mass during every step,
- the work performed to deform the shoe sole,
- the work performed to rotate the shoe sole against the ground,
- energy absorption in the midsole of the shoe, and
- energy lost due to the stiffness in the metatarsal-phalangeal joint.

Using certain assumptions one can estimate the additional mechanical work an athlete must perform (a) against gravity as well as (b) to accelerate the additional mass of the shoe during a marathon. (Note: These two forms of mechanical work are only part of the total additional work. There is additional work, for instance, due to the deceleration of the shoe as well!).

Assumptions:

- The total (physiological) work done by a runner during a marathon is about 2000 to 2500 kcal or about 10^7 J (10 MJ).
- The additional shoe mass is $\Delta m = 100$ g. (Note that this mass is less than the mass of a running shoe. However, at the end of this section results will be presented for different shoe masses).
- Each foot (and shoe) is lifted during each step by $\Delta H = 0.2$ m.
- The maximal speed of the swing leg during the swing phase is 10 m/s corresponding to middle or long distance running.
- The step length (left toe to right toe) is about 2 m, which corresponds to about $n \approx 20{,}000$ steps during a marathon.

Solution of the example:

(a) Additional work due to gravity:
$\Delta W_{gr} = n \cdot \Delta m \cdot g \cdot \Delta H$
$\Delta W_{gr} = 20{,}000 \cdot 0.1\,\text{kg} \cdot 10\,\text{m/s}^2 \cdot 0.2\,\text{m}$
$\Delta W_{gr} = 4000\,\text{J}$

(b) Additional work due to the acceleration of additional shoe mass during each step:
$\Delta W_{acc} = n \cdot ½ \cdot \Delta m \cdot \Delta v^2$
$\Delta W_{acc} = 20{,}000 \cdot 0.5 \cdot 0.1\,\text{kg}\ 100\,\text{m}^2/\text{s}^2$
$\Delta W_{acc} = 100{,}000\,\text{J}$

Comments:

(1) The mechanical work to *accelerate* the additional shoe mass (100,000 J) is about 25 times larger than the additional work to *lift* the additional mass (4000 J).

(2) The additional work due to the additional mass of a running shoe mass of 0.1 kg (104,000 J) corresponds to about 1% of the total physiological work (1,000,000 J). The results for different masses and different maximal foot speeds are illustrated in Figure 2.

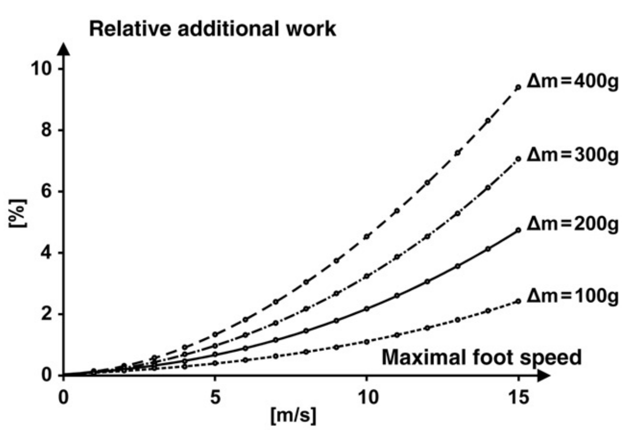

Figure 2. Relative additional mechanical work of an airborne foot due to the acceleration of an additional shoe mass as a function of the maximal foot speed. (From Nigg et al., 2000 with permission of the author.).

(3) As a rule of thumb: The energy demand in running increases about 1% for every 100 g of additional mass on a foot (Frederick 1985).
(4) Based on these estimates one may rethink the times and victories of barefoot runners! Or one may think about shoes, which mimic bare foot running.

It should also be noted that the oxygen consumption of running barefoot can be higher when compared to certain types of footwear (Frederick *et al.* 1983). Depending on shoe sole, treadmill and subject it was found that the oxygen consumption during barefoot running on a treadmill was higher than in some footwear and lower than in other footwear conditions. Thus, when assessing the advantages of barefoot running it is important to understand all variables influencing the energy balance. Although the weight of the shoe has been shown to have an impact, other parameters like midsole density and treadmill surface can also play an important part.

Barefoot and injuries

It has been claimed (a) that people running with running shoes have relatively more running related injuries than people running barefoot and (b) that the running related injuries are typically related to impact forces. These claims will be carefully discussed.

(a) Less running injuries for barefoot running

It seems that the general claim in the scientific literature that people running barefoot have less running related injuries than people running with running shoes originated from a publication in the late 1980s (Robbins and Hanna 1987). In this publication the authors 'have assembled a vast body of data in the form of published and personal reports from educated observers as to running-related type of injury frequency in barefoot populations'. They claim that all the reports and observations consistently point to a low frequency of running-related injuries. One example, states that in populations where barefoot and shod populations co-exist (e.g. Haiti), injury rates of the lower extremities are substantially higher in the shod population (Robbins and Hanna 1987). Furthermore, examples of barefoot runners in international competitions, barefoot runners in underdeveloped countries, comments from a physical education teacher and reports from the West Indies are included.

Since this paper is a major source for the assumption that barefoot runners have fewer injuries than shod runners it should be reviewed very carefully. Here are some concerns:

(1) The difference in the Haiti example may have many different possible explanations. For instance, the differences may be explained with the fact that the barefoot runners in developing countries may be too poor to seek medical attention and that the statistics are influenced by this (Warburton 2001).
(2) Furthermore, it may be that people using shoes in these countries use them because of previous injuries (Warburton 2001).
(3) Additionally, it may be that runners with shoes cover more miles (Warburton 2001) and have more injuries (if at all) for this reason.
(4) It is difficult to determine the surfaces on which people in Haiti run or walk.
(5) The list of 'reports' and 'observations' (Robbins and Hanna 1987) does not include one reference from a scientific study.

We ourselves do not know of any publication that provides hard evidence that people running barefoot have fewer running related injuries than people running with running shoes.

There is one paper that indirectly may have some relevance to this question (Knobloch *et al.* 2008). This group studied chronic and acute Achilles tendon injuries on a sample of 291 elite runners. Among other findings they reported that running on a sand surface increased the relative risk for mid-portion Achilles tendinopathy 10-fold. If barefoot running can be compared to running on sand, these findings would certainly not support the notion that running barefoot results in a lower injury rate than running with shoes. However, even if barefoot running and running on sand can not be compared, these results demonstrate how common expectations are sometimes wrong.

Prospective randomized studies about this question are needed. The current claim that people running barefoot have less running related injuries than people running in shoes is a speculation with no epidemiological support. We suggest that nobody knows at this point in time whether or not people running barefoot have more or less injuries than people running with conventional running shoes.

(b) Running injuries as a result of impact forces

There is no conclusive evidence that impact forces in heel-toe running are associated with an increase in the injury frequency or with a specific running related injury. In this context, the concept that the arch of the foot should act as a shock absorber

(Robbins and Hanna 1987) needs further considerations. The impact force peak occurs at about 30 to 50 ms after contact. For a medium running speed with a ground contact of about 400 ms, the deformation of the arch of the foot is at its maximum at about 200 ms. Thus, the effects of this arch deformation are much too late to act as a shock absorber.

Barefoot products

Compared to shod movement, barefoot movement has many different aspects, including

- the *shape* of the bare foot compared to the shape of the shoe,
- the specific *kinematics* of barefoot and shod movements, and
- the *feeling* of barefoot or shod movement.

Based on such considerations, 'barefoot shoes' have been developed by several manufacturers, suggesting that some of the perceived advantages of barefoot running are transferred into a shod condition. Three new designs using different 'barefoot concepts' discussed in this section include (a) the 'Feet You Wear' concept representing an example where the shape of the shoe is changed towards a barefoot situation, (b) the Nike Free concept where the kinematics of shod running are adapted to the barefoot situation and (c) the MBT (Masai Barefoot Technology) concept where the feeling of barefoot walking and/or running is mimicked.

The Feet You Wear concept (adidas)

The idea of the adidas' 'Feet You Wear' concept was to construct a shoe that mimics the *shape of the human foot*. The human foot is a structure with a rounded shape. The human foot is narrow at the heel and wide in the forefoot. By shaping the shoe like a human foot, the 'Feet You Wear' shoes produced (especially in the rearfoot) smaller levers due to the rounded construction of the shoe sole. The differences were substantial at the heel. Thus, while landing on the heel, the eversion moments are smaller with the 'feet you wear' shoes than with conventional shoes. Consequently, one would expect less foot eversion or pronation, which is commonly assumed to be beneficial. The concept was first introduced in basketball and prospective epidemiological studies with men's teams from the Canadian University Basketball League over a time period of 2 years showed for the 'Feet You Wear' basketball shoes compared to all the other shoes used in this study a significant and substantial reduction of the frequency of injuries (Meeuwisse *et al.* 2003). The injury rate per 1000 athlete exposures was 7.1 for the Feet You Wear shoes and 11.3 for the remaining shoes in the first year and 7.3 and 9.8, respectively, for the second year. Constructional conclusions from the 'Feet You Wear' concept are currently used in several Adidas products (e.g. formotion products).

Nike Free concept

The Nike Free shoes were developed with the goal to mimic the *kinematics of barefoot running*. The Nike Free shoes have a wide and relatively soft heel and a flexible forefoot sole construction. Running in Nike Free shoes results in a flat foot landing typical for barefoot running. It seems that this result is influenced by the wide heel and that the flat foot landing could not be achieved by using a heel shape similar to the human heel. The flexible forefoot construction increases the contact area of the foot, distributing the pressure over a larger area. Furthermore, it forces the foot to be more active than in a conventional shoe. The results of this increased foot activity with the Nike Free shoe on a sample of 100 test subjects showed a significant decrease of 7% in the actual path of motion of the metatarsal-phalangial (MTP) joint during running and an increase in the flexor strength that can be produced in this 'joint' by 20% (Potthast *et al.* 2005).

The same group published epidemiological results for the Nike Free shoes (Brüggemann *et al.* 2008). The comparison included a test group (50 subjects using the Nike Free shoe for 4×30 min per week with moderate physical activity) and a control group (50 subjects with comparable activity but using traditional sport shoes). The test period was 5 months. Ten months after the end of the test period, the test group showed 29% less injuries in the lower extremities (foot, lower leg, knee, thigh, hip and pelvis) than the control group. The mechanism responsible for the reduction of injuries is, however, not understood yet.

Nike VIVO Barefoot Shoes

Another Nike product, the Nike VIVO Barefoot Shoes, has no published literature known to the author evaluating their effectiveness. Reports from recreational runners state that the footwear lack arch support and have an elevated heel, which are both designed to make gait 'more natural'. In addition, the VIVO Barefoot shoes, like the adidas Feet You Wear shoes, have a wide toe box, providing more space for the forefoot.

Earth Footwear Kalso concept

The Earth Footwear brand makes many versions of shoes, including the Kalso. All of their products use the same features, a negative heel technology that positions the toes 3.7 degrees higher than the heels, an anatomic arch support, and BioFoam^{TM} cushioning, which molds to the foot, while (as it is claimed) absorbing shock with each step. A study ('10,000 Steps') funded by Earth footwear, and executed by one of their fitness advisors illustrated the fat-burning benefits, as well as enhanced breathing and endurance with the Earth footwear. More specifically, the average body fat percentage decreased 4 times more in the Earth footwear group than by the non-Earth footwear group, and the Earth footwear group increased their walking speed for a fixed distance more (4.65%) than the non Earth footwear group (2.68%). The original version of the Earth shoe (in the late 1960s) looks similar to the Nike Free shoe. The Earth concept was developed by Anne Kalsö, a Danish Yoga teacher and was a product of the 'Hippie movement' of the 1960s stressing the 'natural' gait.

MBT Masai Barefoot Technology concept

The MBT shoes were developed with the goal to provide a training tool for the foot and leg mimicking the feeling of barefoot movement on soft ground. The MBT shoe is characterized by its rather thick sole with a rounded bottom profile, producing an unstable base during standing (similar to a wobble board). During standing, this unstable shoe characteristic demands increased muscle activity to remain balanced (Nigg *et al.* 2005). Thus, the shoe should be considered as a training device, especially for the small muscles of the foot crossing the ankle joint complex, like the soleus and peroneus longus. Indirect evidence for such a training effect has been provided by the more than 100% increase in balance time when using the MBT shoe over a period of 3 months (Nigg *et al.* 2006). The fact that muscle activity is constantly alternating seems to reduce the joint loading due to muscle co-contraction. However, conclusive evidence for this speculation is still missing. A prospective epidemiological study over 3 months using subjects with knee joint arthritis showed for the MBT and for the control shoe a 25% decrease in subjective joint pain (Nigg *et al.* 2006). A prospective study with golfers with low back pain using the MBT sandals during 6 weeks for training and other daily activities showed a 44% reduction of pain and discomfort after a round of golf. It was speculated that the strengthening of the small muscles seemed to reduce co-contraction and the joint forces in some subjects, which may have been related to a reduction of low back pain.

Other products with rounded soles

The success of the MBT concept was probably the reason for a number of 'new' shoes with similar construction. Examples include (in alphabetical order) Chung Shi, Ethno Walking, Finn Comfort, Ganter, Ryn Walking and Solidus. These shoes have a rounded sole and the manufacturers of these shoes suggest (among other claims) that their products provide a harmonic balance between body, spirit and soul, that they create physiologically correct walking, that they improve blood supply, stimulate the foot muscles and that they produce many other effects. Such claims are often not supported by scientific study results and need careful review.

Summary and concluding comments

The name 'barefoot shoes' is a contradiction in terms. A shoe condition is not a barefoot condition. The discussed 'barefoot shoes' typically take one aspect of barefoot and implement it into a shoe. Some of these aspects are close to barefoot, some need a little stretch. To assume that these shoes correspond to barefoot running or moving is not appropriate and the name 'barefoot shoes' may well be more a marketing strategy than a functional name.

The discussed shoes using a concept of 'barefoot technology' are based on very different conceptual ideas, possibly addressing different aspects of the barefoot locomotion. However, all of them seem to provide a benefit to the athlete, independent on whether they are based on copying the shape of the human foot, the movement during barefoot running or the feeling of barefoot movement on soft ground.

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