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# The Role of Impact Forces and Foot Pronation: A New Paradigm

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**Objective:** This article discusses the possible association between impact forces and foot pronation and the development of running-related injuries, and proposes a new paradigm for impact forces and foot pronation.

**Data Sources:** The article is based on a critical analysis of the literature on heel–toe running addressing kinematics, kinetics, resultant joint movements and forces, muscle activity, subject and material characteristics, epidemiology, and biologic reactions. However, this paper is not a review of the literature but rather an attempt to replace the established concepts of impact forces and movement control with a new paradigm that would allow explaining some of the current contradictions in this topic of research.

**Study Selection:** The analysis included all papers published on this topic over the last 25 years. For the last few years, it concentrated on papers expressing critical concerns on the established concepts of impact and movement control.

**Data Extraction:** An attempt was made to find indications in the various publications to support or reject the current concept of impact forces and movement control. Furthermore, the results of the available studies were searched for indications expanding the current understanding of impact forces and movement control in running.

**Data Synthesis:** Data were synthesized revealing contradictions in the experimental results and the established concepts. Based on the contradictions in the existing research publications, a new paradigm was proposed.

**Conclusion:** Theoretical, experimental, and epidemiological evidence on *impact forces* showed that one cannot conclude that impact forces are important factors in the development of chronic and/or acute running-related injuries. A new paradigm for impact forces during running proposes that impact forces are input signals that produce muscle tuning shortly before the next contact with the ground to minimize soft tissue vibration and/or reduce joint and tendon loading. Muscle tuning might affect fatigue, comfort, work, and performance. Experimental evidence suggests that the concept of "aligning the skeleton" with shoes, inserts, and orthotics should be reconsidered. They produce only small, not systematic, and subject-specific changes of foot and leg movement. A new paradigm for movement control for the lower extremities proposes that forces acting on the foot during the stance phase act as an input signal producing a muscle reaction. The cost function used in this adaptation process is to maintain a preferred joint movement path for a given movement task. If an intervention counteracts the preferred movement path, muscle activity must be increased. An optimal shoe, insert, or orthotic reduces muscle activity. Thus, shoes, inserts, and orthotics affect general muscle activity and, therefore, fatigue, comfort, work, and performance. The two proposed paradigms suggest that the locomotor system use a similar strategy for "impact" and "movement control." In both cases the locomotor system keeps the general kinematic and kinetic situations similar for a given task. The proposed muscle tuning reaction to impact loading affects the muscle activation *before* ground contact. The proposed muscle adaptation to provide a constant joint movement pattern affects the muscle activation *during* ground contact. However, further experimental and theoretical studies are needed to support or reject the proposed paradigms.

**Key Words:** Impact forces—Foot pronation—Injuries, running.

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## INTRODUCTION

Millions of people are involved in running and jogging activities. From those, between 37–56% are injured during the period of 1 year.[1–5] Previous injuries, excessive mileage, excessive impact forces, and excessive pronation have been proposed as major reasons for the development of running injuries.[5–9,11] The sport shoe and sport surface were assumed to influence impact forces and foot pronation. Consequently, the concepts of "cushioning" and "movement (or rearfoot) control" were developed, and strategies were studied to reduce potentially harmful impact forces and foot pronation through appropriate running shoe, shoe insert, and sport surface designs. However, results of recent studies challenged the proposed association between impact forces, foot pronation, and running injuries.

Thus, the purposes of this article are:

- To critically discuss the potential association between impact forces and foot pronation and the development of running-related injuries

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- To synthesize the current knowledge about actual effects of impact forces
- To synthesize the current understanding of factors associated with foot and leg movement during running
- To propose new paradigms for the understanding of the effect of impact forces and movement control during heel–toe running.

## IMPACT FORCES

Impact forces in heel–toe running (Figure 1) are forces resulting from the collision of the heel with the ground, reaching their maximum (the impact peak) earlier than 50 ms after first contact.[10,12] The association of impact forces with musculoskeletal injuries were typically either circumstantial in nature[7] or derived from experiments using animal models.[13] However, many results of running impact-related research studies were unexpected and did not support the concept of impact forces as one prime reason for the onset of running injuries.

Unexpected results were found in biomechanical studies as summarized in Table 1. For instance, it was found that external impact force peaks were not[14,15] or only minimally[16] influenced by changes in the hardness of running shoe midsoles. Similarly, internal impact force peaks in structures of the lower extremities were only minimally and not systematically influenced by running shoe midsoles.[17,18] However, the magnitude of vertical impact force peaks varied substantially (up to 100%) for different running velocities.[19,20] Results from model calculations showed that the magnitude of joint contact forces in the lower extremities are substantially smaller (three to five times smaller) during the impact than during the active phase of running.[18,21–23] Based on these model calculations, it was speculated that normal impact forces occurring during physical activities such as running might not be a major factor in the development of injuries in running.[23]

Unexpected epidemiological results indicated that runners did not show a higher incidence of osteoarthritis than nonrunners.[24–27] Running on hard surfaces did not result in an increase of running injuries if compared with running on softer surfaces.[5] Results of a prospective

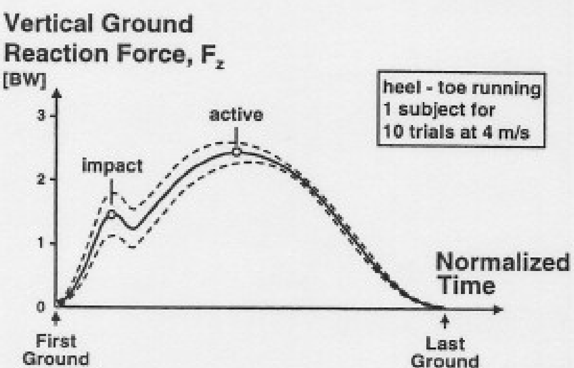


FIG. 1. Illustration of an impact force (mean and SE) in vertical direction for ten trials of one subject running at a speed of 4 m/s.

**TABLE 1.** *Summary of the results for external and internal forces and loading rates for heel–toe running*[14–17,19,20]

| Variable | External | Internal |
|---|---|---|
| Maximal force | Soft ≈ hard | Soft ≈ hard |
| | Barefoot ≈ shod | Barefoot ≈ shod |
| | Impact ≈ active | Impact ≪ active |
| Maximal loading rate | Soft ≪ hard | Soft ≈ hard |
| | Barefoot ≪ shod | Barefoot ≈ shod |

≈, about the same; ≪, much smaller than.

study[12] did not show a significant difference of short-term running injuries between subjects with high-, medium-, and low-impact force peaks (Figure 2). Surprisingly, subjects with a high loading rate in the vertical ground reaction force had significantly fewer running-related injuries than subjects with a low loading rate.[12,28]

Furthermore, in certain cases, selected shock-absorbing insoles reduced the general frequency of injuries.[29,30] However, shock-absorbing insoles were not effective in reducing the incidence of stress fractures in military recruits for which they were originally designed.[29,31] The use of a viscoelastic heel pad was pro-

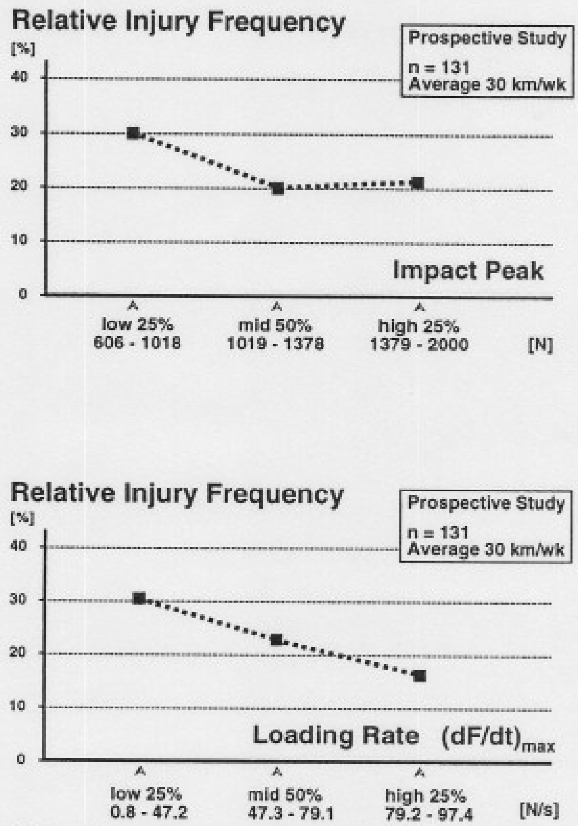


FIG. 2. Relationship between the vertical impact force peak ($F_{zi}$), the maximal vertical loading rate ($G_{zi}$), and the frequency of running-related injuries. The graphs are based on a reanalysis of data from 131 subjects.[28] Their impact forces were assessed at the beginning of the study. A sport medicine physician documented injury occurrences.

posed to be effective in reducing the symptoms of Achilles tendinitis in an athletic population,[32] however, epidemiological evidence for the effectiveness of this strategy has not been provided. These unsystematic epidemiological results for the effect of shock-absorbing insoles suggest that shock absorption might not be the primary reason for the development of these studied injuries.

Biological reactions to impact loading have been studied extensively for cartilage and bone. Impact stimuli have been shown to improve bone integrity. The increase in bone mass could be explained to 68 to 81% by the loading rate applied.[33] Impact activities such as gymnastics, basketball, running, or dancing typically produce an increase in skeletal mass, while athletes involved in low impact activities such as swimming often have a low bone density.[34,35,37] Results from measurements with young female gymnasts showed an increased vertebral bone integrity compared with a moderately active control group.[36] Premenopausal women exposed over a 2-year period to an intensive impact exercise protocol showed a 4% increase in bone mineral density compared with a 1.5% decrease for the nonimpact control group.[38] Results from in vivo experiments showed that the controlled repeated application of a force with a 1 Hz signal frequency could not maintain bone mass over an 8-week period while the same procedure with a 15 Hz signal frequency stimulated substantial new bone formation.[39] If the vertical ground reaction impact forces are simplified as sinusoidal waveforms, their frequency content is generally between 10–20 Hz. These results suggest, therefore, that impact loading has, in general, a positive effect on the development and maintenance of bone, stimulating a greater osteogenic response than nonimpact loading.

The results for cartilage are more difficult to synthesize. Some studies showed negative effects of "impact loading" on cartilage. However, in some cases, the forces applied were active instead of impact forces. Sometimes, the stresses applied were much higher than those experienced in an athlete's knee during running, and/or used loading regimens were often rather severe.[13,40–43] Furthermore, assuming that cartilage adapts to the stresses acting on it, it would be reasonable to expect different effects of this impulsive loading regimen in the rabbit, a fairly sedentary animal, than in humans, who have had many years to adapt to running-related loading.[44] Experimental results from studies with no methodological concern by the author show nonconsistent results for cartilage. High loading rates showed an increase of cartilage damage in impact experiments, compared with low loading rates.[43,45] However, high performance female gymnasts showed an increase in strength of the intervertebral discs, compared with a paralleled group of moderately active females.[36] Thus the results of these studies are not conclusive when explaining the possible effects of impact loading on cartilage.

Based on these research results, one cannot conclude that impact forces are an important factor in the development of chronic and/or acute running-related injuries. Excessive impact forces may produce damage to the human musculoskeletal system. There is a window of loading in which biologic tissues react positively to the applied impact loads. Based on the current knowledge, it is speculated by the author that impact loading for bone, cartilage, and soft tissue structures falls within the acceptable window for moderate and intensive running. It is further speculated that impact loading for bone may sometimes fall outside the acceptable window for intensive running with too-short recovery periods. However, the knowledge based on these speculations is limited.

The summary of biomechanical and epidemiological results indicates that the concept of "impact forces" as a major source for running injuries is not well understood, and that the paradigm of "cushioning" to reduce the frequency or type of running injuries should be reconsidered.

**Further Biomechanical Considerations**

The experimental results indicate that each runner adapts to changes in shoes or surfaces. The impact forces acting on the human foot and leg can be influenced by changing the foot and leg geometry, ankle and knee joint stiffness, and/or the coupling between the soft and rigid structures of the leg.[46,47] The response of the locomotor system may well be a combination of the three strategies. The strategies of foot/leg geometry and joint stiffness have been discussed earlier.[48] However, the strategy of changing the coupling between the soft and rigid structures of the runners leg, the strategy of muscle tuning, has only recently been proposed.[12]

The muscle tuning concept suggests that the impact forces during heel strike should be considered as an input signal, characterized by amplitude and frequency. This impact force signal could produce bone vibrations at high frequencies and soft tissue vibrations of the human leg (e.g., triceps surae, quadriceps, or hamstrings muscles) at frequencies that might concur with the frequencies of the input signal. Thus soft tissue vibrations are of particular interest in this context because resonance effects could occur. Such soft tissue vibrations would cost energy, would not be comfortable, and are typically very short and heavily damped during running for muscular soft tissues. Thus, it is proposed that the muscles attempt to avoid vibrations of the soft tissue by using a tuning strategy. The concept proposes that muscles would be preactivated to create a damped vibrating system. If this assumption were correct, one would expect a change in the electromyographic (EMG) signal.

Results from pilot studies in our laboratory seem to support this speculation.[12,49] Muscle activity was quantified for selected muscles using EMG sensors. Three subjects were asked to run on three surfaces with distinctly different hardness: concrete, a normal synthetic track surface, and a soft synthetic warm-up surface. The measured EMG signal was analyzed with respect to its power spectral density and its frequency content. The results of this pilot study showed a systematic change in the power spectral density and in the median frequency for all three subjects (Figure 3).

Since this preactivation requires energy, one would expect that different shoe sole or surface material properties would require different amounts of work when performing a specific task such as running. Such a result has been theoretically predicted with an arbitrarily defined biomechanical model in which the mechanical properties of the shoe–surface interface were systematically varied.[50] The results for one set of system characteristics (Figure 4) suggested that soft and viscous materials require less work than hard and elastic ones for this specific set of characteristics.

Furthermore, one would expect that the required energy in a specific shoe situation would be subject specific since the necessary vibration damping would depend on the characteristics of the input signal and on the vibration characteristics of each soft "tissue package" (e.g., hamstrings) of a subject. Pilot results from initial experimental work support this line of thought. Ten subjects were exposed to treadmill running with $VO_2$ quantification (measurements on four different days) in two different shoe conditions. The shoes were identical except in the material of the heel. One shoe had an elastic heel material, the other a viscous heel material. The results (Figure 5) indicate that the required work is subject and shoe specific and that the differences could be as high as 5%. Thus, the different "feeling"w hile running on soft or hard surfaces or shoes may be associated with changes in muscle activities and related changes in the soft tissue vibrations, both influenced by the impact input.

### A Proposed New Concept/Paradigm for Impact Forces: Muscle Tuning

Based on the above considerations, a new concept/ paradigm for impact forces during running is proposed:

- Impact forces are an input signal into the human body.
- This signal produces a reaction of the muscles (muscle tuning).

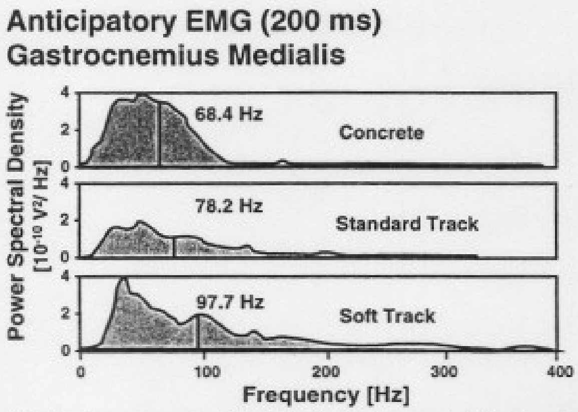


**FIG. 3.** Power spectral density of electromyographic signals measured while running on three different surfaces, hard (concrete), medium (standard synthetic track), and soft (synthetic warm-up track) for one specific subject. Data from a pilot study in the Human Performance Laboratory.[20,49]

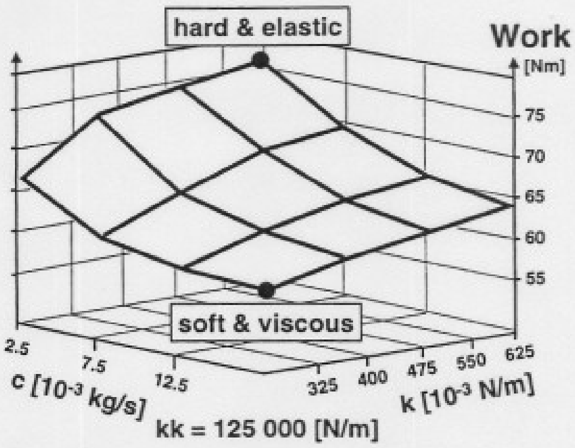


**FIG. 4.** Work required per step cycle for systematically varied spring and damping constants.[50] The springs and dampers represent the mechanical properties of the sport surface/shoe.

- The muscle tuning occurs shortly before the next contact with the ground.
- The cost function for this muscle reaction is to minimize soft tissue vibration.
- Based on the input signal and the subject-specific characteristics, muscle tuning can be low or high.
- Thus muscle tuning might affects fatigue, comfort, work, and performance.

Thus, impact forces during normal physical activity are not important because of potential injuries but rather because they affect fatigue, comfort, work and performance. Thus, it is proposed that muscle tuning is the dominant response of the human locomotor system to impact loading. The theoretical and experimental evidence for the proposed model is certainly not sufficient.

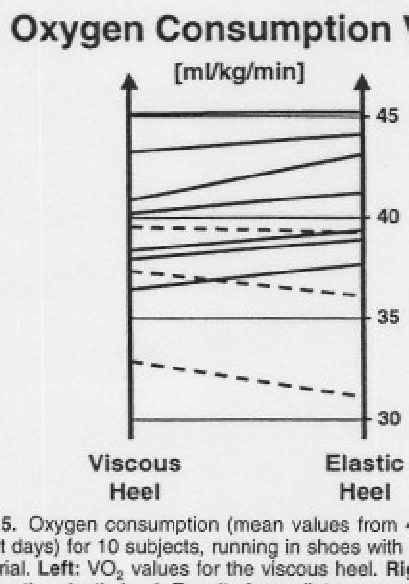


**FIG. 5.** Oxygen consumption (mean values from 4 trials at different days) for 10 subjects, running in shoes with different heel material. **Left:** $VO_2$ values for the viscous heel. **Right:** $VO_2$ values for the elastic heel. Results from pilot measurements in the Human Performance Laboratory.

However, further research should be used to solidify or reject the proposed new paradigm.

## MOVEMENT CONTROL

Running-related injuries have often been associated with the static or dynamic malalignment of the skeleton. Excessive foot varus or valgus positions have been speculated to create high loading situations and for repeated loading cycles overuse injuries. Additionally, excessive foot eversion and/or tibial rotation movements have been proposed to increase the chance of overuse syndromes such as patellofemoral pain syndromes, shin splints, Achilles tendinitis, plantar fasciitis, and stress fractures.[2,6,7] Thus the proper alignment of the skeleton has been proposed as being one of the most important functions of running shoes, shoe inserts, and orthotics. It has been proposed that overuse injuries due to excessive foot and leg movement, specifically due to excessive foot eversion, could be reduced with special shoes, shoe inserts, or orthotics by correcting, aligning, or limiting the skeletal movement of foot and leg. The postulated effects of such interventions were documented in clinical studies with the treatment and rehabilitation as the variables of interest, and in biomechanical studies with the changes in foot and leg movement as the variables of interest. The results of these studies are critically discussed and summarized in the next few paragraphs.

The support of the medial foot arch has often been proposed as one of the most important correction strategies for foot eversion/pronation. Some studies determined the effect of the positioning of such a medial arch support. Clinically two strategies were proposed,[51] a support under the arch of the foot (anterior support) and a support under the sustentaculum tali (posterior support). A medial arch support positioned from posterior to anterior (Figure 6) showed a mean reduction of about 4–5° for the initial shoe/leg eversion (eversion velocity) if compared with the condition with no medial support. However, no significant changes between medial support and no support were found for the total foot eversion.[52,53]

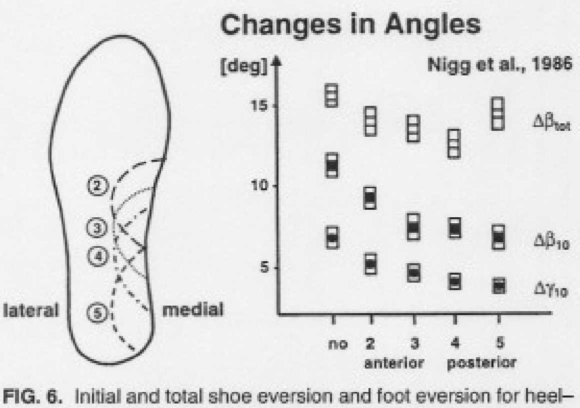


FIG. 6. Initial and total shoe eversion and foot eversion for heel–toe running without and with a medial support. The position of the medial support was systematically changed from posterior, under the sustentaculum tali, to anterior, under the arch of the foot.[52]

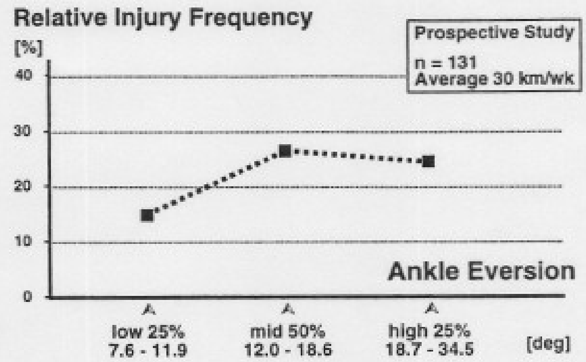


FIG. 7. Injury frequency as a function of leg eversion during heel–toe running. Rearranged and reanalyzed results from a previous prospective study[28] of runners over a 6-month period.

Soft, semirigid, and rigid orthotics built to reduce foot/leg eversion and/or tibial rotation were studied by various groups. Movement corrections produced by such interventions were maximally between 2–4°.[54–58] The results of these studies showed generally small and nonconsistent reductions in foot and leg movement amplitudes for the tested interventions. Nevertheless these results were used to imply that shoe inserts or orthotics change (align) the skeletal movement or position.

However there are several experimental results, which suggest that the concept of "aligning the skeleton" with shoes and shoe inserts/orthotics should be reconsidered. First, in an epidemiological study, the lower extremity alignment was suggested not to be a major risk factor for running injuries based on alignment measurements[59] on a group of runners enrolling in a marathon training program. Second, results from a prospective study in our laboratory, with 131 runners and an average running distance of 30 km per week, showed that foot and ankle joint alignment and movement did not act as a predictor for an increase in running injuries over a 6-month period (Figure 7).

Third, results from a study using 12 subjects and 5 inserts with identical shape but different materials showed typically small, nonsystematic changes in foot and leg alignment and movement.[60] Inserts produced for some subject–insert combinations a reduction in foot and leg movement, for others a reduction in foot movement and an increase in leg movement, and for a third group an increase in foot movement and a decrease in leg movement. The results of this study indicate that use of an insert/orthotic is subject specific. Additionally they show that the functioning of a "good" insert/orthotic is not well understood.

Fourth, results from studies with bone pins in the calcaneus, the tibia, and the femur showed only small, nonsystematic effects of shoes or inserts on the kinematics of these bones during running.[63] Even more surprising, the differences in the skeletal movement between barefoot, shoes, and shoes with inserts were small and nonsystematic. The results of this study suggest that the locomotor system does not react to interventions with shoes, inserts, or orthotics by changing the skeletal movement pattern. These experimental results do not provide any evidence for the claim that shoes, inserts, or orthotics align the skeleton. Based on the results of the bone pin study for shoes and shoe inserts[63] one may even challenge the idea that a major function of shoes, shoe inserts, or orthotics consists in aligning the skeleton.

The previous paragraphs provided evidence contrary to the traditional concept that shoes, inserts, and orthotics align the skeleton. The skeleton seems to change its path of movement for a given task only minimally when exposed to an intervention (shoe, insert, or orthotic). One could argue (and support this argument with evidence) that—for a given task—the locomotor system chooses a strategy to keep the skeletal movement in a constant path. A similar "minimal resistance movement path" has been discussed earlier for joint movement.[62] The neuromuscular system is programed to avoid any deviation from this path. Thus, appropriate muscles will be activated if any intervention tries to produce a different skeletal movement. An optimal shoe, insert, or orthotic would minimize additional (not task related) muscle work. Consequently, shoes, inserts, and orthotics would affect muscle work, which should affect fatigue, comfort, and work/performance. Thus if comfort is an indicator for muscle activity, wearing comfortable shoes should require lower oxygen consumption than wearing uncomfortable shoes. Pilot evidence for these effects has been quantified. For instance, oxygen consumption measurements for 10 subjects running in a most and a least comfortable shoe (chosen out of five shoes provided) showed a significant difference, with more oxygen needed for running in the least comfortable shoe (Figure 8).

Thus, the behavior of a subject in a given situation (movement task and footwear) is determined by a set of factors: A force signal acts as an input variable on the shoe.

- The shoe sole acts as a first filter for the force input signal.
- The insert or orthotic acts as a second filter for the force input signal.

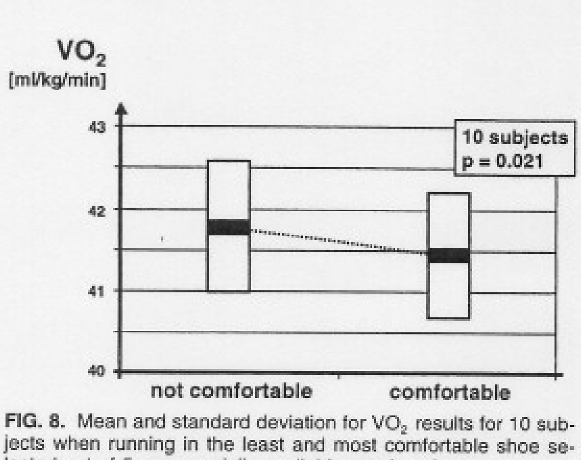


**FIG. 8.** Mean and standard deviation for $VO_2$ results for 10 subjects when running in the least and most comfortable shoe selected out of 5 commercially available running shoes.

- The plantar surface of the foot with its mechanoreceptors senses the force–input signal.
- The signal information is transferred to the central nervous system, which provides a dynamic response based on the subject-specific conditions.
- The subject performs the movement for the task at hand.

The first three steps are situation dependent and can be influenced by the selection of the movement task, the shoe, and the insert or orthotic. The last three steps are subject dependent. The sensitivity for the mechanical signals, the potentially wobbling soft tissue masses, and the cost functions for the movement selection may be different for each subject–shoe-insert condition. This line of reasoning could explain the small and nonconsistent changes in foot and tibia movement between barefoot, shoes, and shoes with inserts[63] and the highly subject-specific differences in oxygen consumption when running with viscous or elastic heels (Figure 5). However, the experimental results and the theoretical consideration illustrate that the knowledge of the subject-specific characteristics and the appropriate insert strategies are important pieces of information for a podiatrist or orthotist when preparing an insert or orthosis for an athlete or a patient.

### A Proposed New Concept/Paradigm for Foot Pronation and Movement Control

Based on current state-of-the-art knowledge, a new concept/paradigm for foot pronation is proposed:

- Forces acting on the foot during the stance phase act as an input signal.
- The locomotor system reacts to these forces by adapting the muscle activity.
- The cost function used in this adaptation process is to maintain a preferred joint movement path for a given movement task (e.g., running).
- If an intervention supports the preferred movement path, muscle activity can be reduced. If an intervention counteracts the preferred movement path, muscle activity must be increased. An optimal shoe, insert, or orthotic reduces muscle activity.
- Thus shoes, inserts, and orthotics affect general muscle activity and, therefore, fatigue, comfort, work, and performance.

Thus, "movement control" during the stance phase is not important to align the skeleton but rather because strategies to control movement change muscle activity during the stance phase. This change in muscle activity (that is not related to the actual movement task) might affect fatigue, comfort, work, and performance.

However, the presented concept/paradigm for the function of shoes, inserts, and orthotics needs more evidence and stronger evidence to support or reject it.

## SYNTHESIS

The two aspects of running biomechanics, "impact" and "movement control," have been discussed, and a new way of thinking about them has been introduced. The proposed solution suggests that the locomotor system use a similar strategy in both situations, "impact" and "movement control". In both cases the locomotor system keeps the general kinematic and kinetic situation similar for a given task. To deal with impact forces, the muscles are pre-tuned to possibly minimize soft tissue vibrations. This strategy affects the muscle activation before ground contact. To deal with shoes, inserts, and orthotics, the muscles are activated (if necessary) to provide a constant joint movement pattern. This strategy affects muscle activation during ground contact.

The characteristics of individual subjects with respect to resonance frequencies of soft tissue packages and preferred joint movement paths are different. Thus, subject-specific reactions to shoes, inserts, and orthotics are experimentally measured. However, there is some initial evidence that the signal–response pattern is similar for groups of subjects. The goal of future research should be to match subject characteristics (foot shape, lower extremity alignment, muscle strength, joint compliance, foot sensitivity, etc.) with shoe, insert, and orthotic characteristics (material properties, shape, time behavior, etc.) to find optimal group solutions for shoes, inserts, and orthotics. Based on initial results it is suggested that the needs of a large segment of the population can be served with four to five specific groups.

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