

Benno M. Nigg, Maurice M. Mohr & Sandro R. Nigg – New paradigms in running injury prevention

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Editorial

Tilp (Ed.): Benno M. Nigg, Maurice M. Mohr & Sandro R. Nigg –
New paradigms in running injury prevention CISS_2019.100

Main Article

Nigg, Mohr & Nigg: Muscle tuning and preferred movement path – a paradigm shift CISS_2017.007

Commentaries

Becker: New Hypotheses and Unanswered Questions in Running Injury Research –
comment on Nigg et al. CISS_2018.102

Clark, Udofa, Ryan & Weyand: Running impact forces: from half a leg to holistic understanding –
comment on Nigg et al. CISS_2018.107

Federolf, Doix & Jochum: A discussion of the Muscle Tuning and the Preferred Movement Path concepts –
comment on Nigg et al. CISS_2018.103

Hamill, Boyer & Weir: A paradigm shift is necessary to relate running injury risk and footwear design –
comment on Nigg et al. CISS_2018.104

Paquette & Miller: Reconciling new with old injury paradigms and the need to dig deeper –
comment on Nigg et al. CISS_2018.105

Vanwanseele, Zhang & Schütte: Muscle tuning and preferred movement path: do we need a
paradigm shift or should we redefine the old? – comment on Nigg et al. CISS_2018.106

Response

Nigg, Mohr & Nigg: Response to select comments on the proposed paradigm shifts in running CISS_2019.001

Benno M. Nigg, Maurice M. Mohr & Sandro R. Nigg – New paradigms in running injury prevention

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Target articles are special features in the *Current Issues of Sports Science* (CISS, founded in 2016) that appear once a year. These articles should provide an overview about a sport scientific topic authored by a highly renowned scientist. We are very proud that the second target article of the journal was provided by Benno M. Nigg and his co-authors Maurice M. Mohr and Sandro R. Nigg.

Already in 1976 Prof. Benno M. Nigg published first studies about biomechanical analyses of sport surfaces for track and field and games and the interaction with the athlete (Nigg, 1976). During the next 40 years Prof. Nigg dedicated a great part of his research to analyze the causes for sport- and running injuries. Prof. Nigg did not only personally witness several scientific approaches on the prevention of running injuries but was on the forefront in the development of approaches like the “impact force”- and the “pronation control”-paradigm on this topic himself (Nigg & Lüthi, 1980). These paradigms initiated a central research field on the biomechanics of running and affected the development of running footwear over the years substantially. It is remarkable and proofs the ongoing development of sports science that Prof. Nigg and his co-authors now

ABSTRACT

In this target article (TA; CISS_2017.007), Benno M. Nigg, Maurice M. Mohr, and Sandro R. Nigg explain and criticize the two main paradigms (‘impact’ and ‘pronation’) in running injury prevention research of the last 40 years and present new paradigms on ‘muscle tuning’, ‘preferred movement path’, and ‘functional groups’. The main article (CISS2_017.007) is then discussed by six peer commentaries (CISS_2018.102 – CISS_2018.107), authored by sport scientists that are experts in the field. Finally, critiques, suggestions, and extensions brought forward by the commentators are acknowledged by Nigg and co-authors in their closing response (CISS_2019.001).

provide novel paradigms in running injury prevention in their current article (Nigg et al., 2017).

The complete target article consists of the main article, six invited comments on this article by expert research groups from all over the world, and a response by the authors on these comments.

In their main article, Nigg and co-authors provide an historical overview about the main paradigms on running injury prevention “impact force” and “pronation control” and provide arguments why these paradigms should be abandoned due to a lack of biomechanical and epidemiological evidence. They criticize the lack of a “gold standard” to quantify foot pronation and suggest undertaking longitudinal studies with large sample size where running injuries are tracked and correlated with individually determined external and internal loading variables. Furthermore, they present alternative paradigms: “Muscle tuning” and “preferred movement path”. Impact forces are input signals characterized by amplitude, frequency, and time. The idea of muscle tuning is that the CNS responds in a way to minimize soft-tissue vibrations which is especially important for performance, fatigue, and comfort when the input

frequency and the natural frequency of the soft-tissue compartment are close. The preferred movement path is based on the observation that many studies showed that the skeletal kinematics change only minimally when exposed to a change in shoe, insert, and/or orthotic. This can be interpreted as a strategy of the CNS to keep the skeletal system in an individual standard (preferred) path. Consequently, Nigg and co-authors suggest designing footwear in a way to facilitate the individual preferred movement path such that the energy for propulsion is kept minimal. Finally, it is proposed to relate groups of runners with similar reaction on footwear interventions into “functional groups” to connect the characteristics of shoes with the characteristics of subjects.

Six international researchers or research groups (Becker, 2018; Clark, Udofa, Ryan, & Weyand, 2018; Federolf, Doix, & Jochum, 2018; Hamill, Boyer, & Weir, 2018; Paquette & Miller, 2018; Vanwanseele, Zhang, & Schütte, 2018) added their perspective on the main article. The main points brought up by these researchers regarding classical paradigms were that i) external impact forces have not been assessed and interpreted correctly and their relationship with internal loading is still not well understood and ii) traditional ways of assessing foot pronation do not represent foot movement well and therefore are not adequate to investigate running injury. Both paradigms should therefore be re-evaluated but not necessarily abandoned while the novel paradigms from Nigg et al. (2017) are valuable additions to the field of the biomechanics of running injuries (Becker et al., 2018). Both old and novel paradigms should be in the focus of future work on running injuries (Paquette et al., 2018).

In their response to the comments, Nigg et al. (2017) agree on the shortcomings of traditional variables on external impact loading and pronation and point out the need to investigate internal (i.e. tissue) loading and related tissue adaptation on an individual level using specific hypotheses. They furthermore propose to structure future running injury research in a) studies with small sample sizes under controlled conditions to identify the relationship between external and internal loading and b) large epidemiological studies that use these identified external variables for injury-specific research.

Altogether, the target article augments the position on running injury research substantially, questioning current theories and developing new theories. This target article demonstrates the strength of scientific dialectic in the development of new paradigms that are the basis for future knowledge in sports science.

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All relevant data are within the paper.

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Muscle tuning and preferred movement path – a paradigm shift

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ABSTRACT

In the last 40 years, the scientific debate around running injuries and running shoes has been dominated by two paradigms, the 'impact' and the 'pronation' paradigms. However, the development of running shoe technologies aimed at reducing impact forces and pronation has not led to a decline of running-related injuries. This article recommends to abandon the 'impact' and 'pronation' paradigms due to a lack of biomechanical and epidemiological evidence and instead suggests a shift to new paradigms: 'Muscle tuning' and the 'preferred movement path'. These paradigms represent new approaches to understanding the biomechanical patterns of each individual runner and how they are controlled by the neuromuscular system. Experimental evidence in support of the 'muscle tuning' and 'preferred movement path' paradigms are presented and discussed regarding their relevance for running performance, injuries, and footwear. Finally, this paper proposes that the concept of 'functional groups' should be used and further developed to overcome the challenge that groups of individuals respond differently to footwear interventions. First, groups of individuals who behave similarly (functional groups) should be identified. Second, running shoes should be selected to match the characteristics of the identified functional groups in order to optimize the beneficial effects of running shoes for improving running performance and reducing the risk of running injuries.

Keywords:

Running injuries – running shoes – impact forces – pronation – functional groups

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Nigg, B. M., Mohr, M. & Nigg, S. R. (2017). Muscle tuning and preferred movement path – a paradigm shift. *Current Issues in Sport Science*, 2:007. doi: 10.36950/CISS_2017.007

Introduction

In the last about 40 years running and running shoe discussions were dominated by two paradigms, the 'impact' and the 'pronation' paradigms. This paper will critically review these two paradigms and will suggest that they should be abandoned because there is not enough epidemiological and functional evidence to support them. In addition, this paper will also propose some new paradigms replacing the old paradigms of 'cushioning' and 'pronation', and a further suggestion for how to methodologically and conceptually investigate running performance and running injuries. Finally, this paper proposes that the concept of "functional groups" should be used and further

developed to understand running, running performance and running injuries.

The Impact force paradigm

An impact occurs as a result of a collision between two objects. In heel-toe running, an impact occurs because of the collision between the heel of the foot and the ground. In forefoot running, the impact occurs because of the collision between the forefoot and the ground. In heel-toe running the impact force peak is a result of the deceleration of the foot and part of the leg. In forefoot running, the impact peak is a result of the decel-

eration of part of the foot. The impact force peaks are evident in the vertical ground reaction force-time curves (Fig. 1). The vertical impact peaks increase with increasing running velocity (Nigg, Bahlisen, Luethi, & Stokes, 1987) as illustrated below. Note that impact peaks may also be present in the a-p and m-l directions (Nigg, 2010). However, it is the vertical component of the impact force peaks that is the highest peak and that has been extensively discussed in the scientific literature.

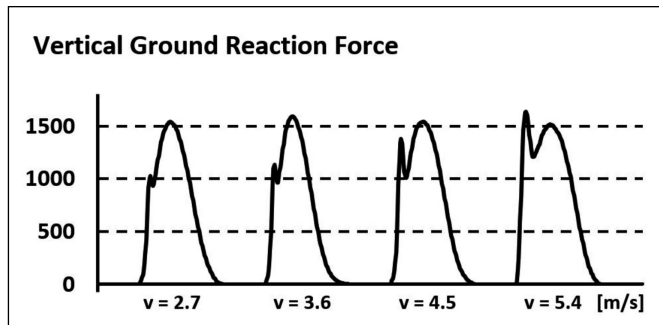


Figure 1: Illustration of the vertical impact force-time curves for one subject during heel-toe running at 4 different running velocities.

Since the majority of runners execute a heel-toe running style (Kerr, Beauchamp, Fisher, & Neil, 1983; Larson et al., 2011), this paper will focus on this type of running. When analyzing forces during running, one should study external and internal forces for both the impact and active parts of ground contact. As a result, there are four candidates that could be considered as contributing to the risk of developing a running injury: external and internal peak forces and peak loading rates. From a functional perspective, the internal variables are most important as they are more related to the mechanical loading at the tissue level. However, historically only the external impact forces and loading rates have been discussed in the scientific literature and have been used to develop the “impact force” paradigm.

From these discussions, the external impact forces have been considered dangerous (Daoud, Geissler, Wang, Saretsky, Daoud, & Liebermann, 2012; Hreljac, Marshall, & Hume, 2000; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Nigg, Cole, & Brüggemann, 1995; Shorten, 1993; Shorten, 2000; Shorten, & Winslow, 1992; Zifchock, Davis, & Hamill, 2006;) and have been assumed to be the reason for the development of many running related injuries and the following paradigm was developed (Nigg & Lüthi, 1980): *External impact forces should be reduced since they are one possible reason for running related injuries.*

There are functional and epidemiological reasons for why the impact force paradigm is not appropriate.

Functional reasons: First: The forces that may be associated with the development of injuries are the forces acting on internal structures. Such internal forces have been estimated with model calculations by several researchers (Burdett, 1982; Harrison et al., 1986; Morlock, 1990; Scott & Winter, 1990). For running, all model calculations consistently showed (a) that the internal active forces in the lower extremities are substantially

(200 to 600 %) higher than the internal impact forces (b) that internal loading rates were typically higher for the active than for the impact phase and (c) that there is little correlation between the external and the internal forces. Thus, one should not expect injury indications from external forces. Further, if internal forces, loading rates, stresses or strains would be the reason for injuries, one should expect injuries primarily for the active phase. However, such active phase injuries have not been identified yet. Second: Internal and external impact forces and loading rates increase with increasing running speed (see Fig 1). Consequently, one should expect more impact related injuries for faster than for slower runners. However, there is no convincing evidence for a relationship between running speed and injury frequency (Mechelen 1992).

Epidemiological reasons: A summary of the epidemiological results has been published earlier (Nigg, Baltich, Hoerzer, & Enders, 2015). In short: No significant results were found in any of the reviewed epidemiological studies on impact loading and running injuries. The major shortcoming of all impact related injury studies is that the number of test subjects is way too small. Out of 15 considered studies three had a sample size of more than 50 test subjects and the remaining 12 studies had an average sample size of 27 test subjects. Thus, there are no conclusions possible due to these methodological shortcomings.

Conclusion

There are no functional and/or epidemiological results that would allow any statement of support for the notion that impact loading and running injuries are associated with the development of running injuries and that the impact paradigm is valid. In order to fully address/understand the possible relationship between impact loading and running injuries, longitudinal, prospective studies with large sample sizes should be conducted, where running injuries are tracked and correlated with all four variables of loading, internal and external and active and passive at baseline. Such studies should include individual analyses where the internal loading of the participants would be determined. Using these data, possible relationships between running injuries and external or internal forces could be re-evaluated. Until such studies have been conducted, the authors suggest that the impact paradigm should not be used for discussions about the connection between running shoes and running injuries.

Are impact forces important for understanding running related questions?

The conclusion related to external impact forces and injuries suggests that increased external impact forces and loading rates most likely are not the reason for the development of specific injuries. The question, however, is whether impact forces are important because of some other aspects. This next section addresses this question. At the time when we came to the conclusion that external impact forces are not the reason for run-

ning related injuries we went back and studied the movement of the lower extremities during landing. We knew at that time that running shoes that lead to different impact forces produce different comfort feelings (Miller, Nigg, Wen, Stefanyshyn, & Nurse, 2000). Thus we concluded that there should be differences in kinematics, kinetics, muscle activity or some other running specific variables when running in different shoes. The first (surprising) result of this renewed approach was that the soft tissue compartments of the lower extremities did not vibrate substantially as would be expected for a freely oscillating system. The soft tissue compartments are made up of muscles and other non-active materials. If they are vibrating less than expected, we suggested that they must be damped. Active damping, however, could only be provided through muscles and it has been demonstrated that muscles are quite good in doing this (Wilson, McGuigan, Su, & van den Bogert, 2001). Thus, we proposed that muscles are used to damp the unwanted and possibly excessive vibrations of soft tissue compartments. Experimental results showed that soft tissue compartments were vibrating systems, which, in a first approximation, could be characterized with a natural frequency and a damping coefficient (Wakeling & Nigg, 2001). Note that:

- (a) The natural frequencies and damping coefficients may typically be different (often small differences) in the three axis directions, which may produce beat effects in the movement of soft tissue compartments (superposition of two oscillations with close frequencies).
- (b) The natural frequencies and damping coefficients are influenced by the level of muscle activation. The differences between the natural frequencies and the damping coefficients between a totally relaxed and a maximally contracted quadriceps and triceps surae were close to 100 %.

When studying the reaction of vibrating systems one often thinks of resonance phenomena. To analyze the question whether resonance plays a role during human locomotion one should consider mechanical model calculations as well as experimental results. The question to be answered is whether having shock input signals with a frequency close to the natural frequency of a soft tissue compartment will affect the preparation and execution of locomotion differently compared to an input frequency further away from the natural frequency of the soft tissue compartments.

Model considerations

Resonance occurs when a mechanical vibrating system is exposed to a continuous vibration input with the same frequency as the natural frequency of the vibrating system. However, it has been proposed, using a simple mechanical spring-damper model for a shock type input, that no resonance phenomena will take place (Kaiser, 2016). Thus, the author of this work suggests that muscle tuning doesn't occur during heel-toe running and that changes in EMG are rather an effect of changes in the landing geometry of the foot/shoe. Looking at the human

locomotor system as a purely mechanical system one can argue that the impact related oscillations are completely damped before the next shock occurs. In this case, resonance should not be a problem. In the situation, however, where this is not the case, where vibrations are still existing, one should expect resonance phenomena. That may be especially true for fast running and/or for subjects with a low muscle tonus. However, to understand this question, the human body should be considered as a neuro-muscular control system as illustrated in the next paragraphs.

Experimental evidence

In an experiment using a vibration platform that produced a shock-type force signal this question has been addressed (Wakeling, Nigg, & Rozitis, 2002). In this experiment, the subject was standing on the toes while exposed to specific force shock inputs (Fig 2).

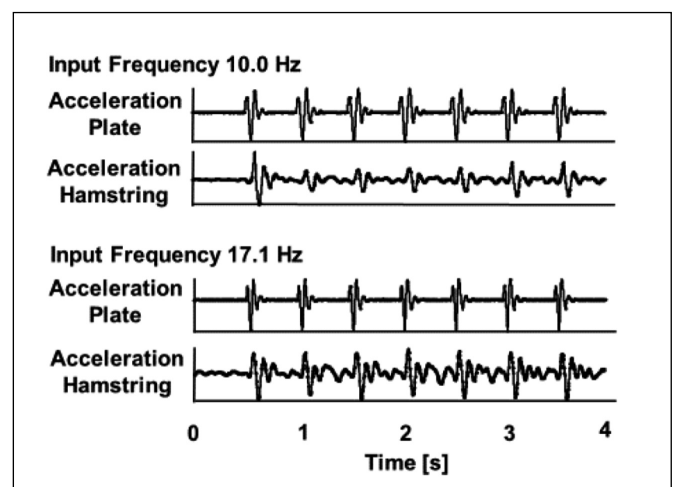


Figure 2: Hamstring acceleration as a function of a shock force input while standing on the toes on a vibration platform. The natural frequency of the soft tissue compartment “hamstrings” was determined as 12.6 Hz. The force input signals were single displacements at frequencies of 10.0 Hz (signal 1) and 17.1 Hz (signal 3). The corresponding accelerations of the hamstring soft tissue compartment are just below the input acceleration signals of the vibration plate (signal 2 and 4). (Derived from data from Wakeling et al., 2002).

The results of this experiment show that the input force signal with a frequency slightly lower than the natural frequency (top signal) produces a different reaction (second signal from top) than the input force signal with a frequency substantially higher than the natural frequency of the soft tissue compartment (bottom two signals). The acceleration of the soft tissue compartment closer to the natural frequency of the soft tissue compartment is immediately damped while the acceleration for the input frequency farther away is not damped at all.

As muscle activity is changing as a reaction of different input signals, these experimental results suggest that the human locomotor system assesses the frequency components of the input signal and reacts by damping when they are too close to the resonance frequency of the soft tissue compartment. These results are in agreement with more recent, similar experiments (Di Giminiani, Masedu, Padulo, Tihanyi, & Valenti, 2015; Perchthaler, Horstmann, & Grau, 2013; Pollock, Woledge, Mills, Martin, & Newham, 2010). In consequence, a purely mechanical consideration of the corresponding effects is not appropriate and that maybe the neuro-motor control aspect must be considered together with the purely mechanical effect. However, it is also evident that there is much more research needed to understand these phenomena completely. The experiments were quasi-static and the models were purely mechanical. Oscillations can be influenced by changing the natural frequency or by changing (increasing) the damping. In all the published and not published results of our group (Boyer & Nigg, 2004; Enders et al., 2012; Nigg, 2010; Wakeling et al., 2002) the strategy to increase the damping was the preferred strategy when compared to shifting of the natural frequency. Thus, it is suggested that damping is one of the preferred strategies when dealing with unwanted oscillations of soft tissue compartments.

In summary:

- Soft tissue compartments of the human locomotor system are vibrating systems that can be described with a natural frequency and a damping characteristic.
- The damping of the soft tissue compartments is different for input signals close to compared to far away from the natural frequency of the soft tissue compartment. The damping is higher for input signals close to the natural frequency.
- Damping is the preferred strategy for the reduction of soft tissue compartment oscillations as opposed to shifting the natural frequency.
- Damping can be influenced by changing the activation of the involved muscles.

Muscle Tuning – A New Paradigm

Based on these considerations, a new paradigm for understanding the reactions of the human locomotor system to repetitive impact forces is proposed (from Nigg, 2010, p. 54):

- Impact forces are an input signal characterized by amplitude, frequency, and time.
- These signals are sensed and, if necessary, the CNS responds by adjusting (tuning) the activation of corresponding muscle groups.
- Tuning occurs to minimize soft-tissue vibrations.
- The effects of muscle tuning are high when the input frequency and natural frequency of a specific soft-tissue compartment are close.
- The effects are subject specific and depend on the characteristics of every single soft-tissue compartment.

- The effects of muscle tuning should be seen in the performance, fatigue, and comfort characteristics of specific impact/subject combinations.

Experimental evidence for “muscle tuning” for continuous oscillations in a quasi-static situation has been provided earlier (di Giminiani et al., 2015; Nigg, 2010; Perchthaler et al., 2013; Wakeling et al., 2002;). The results show a high correlation between the frequency response and the muscle activity response, a result that would have been predicted based on the new paradigm.

Experimental evidence for an actual running situation is more difficult to provide. It has been attempted earlier (Boyer & Nigg, 2004) and it was shown that muscle activity is in fact tuned in response to running conditions that produce different impact scenarios (e.g. shoes with different midsole hardness). However, the results could be interpreted in different ways. One interpretation for the change in EMG activity could be that when running in shoes that lead to higher loading rates and the input signal frequency approaches the natural frequency, the muscle activity increases. Another interpretation of the results could be that when changing the shoe characteristics one changes the joint moments (especially for the ankle joint), which may demand a change in muscle activity. The current data don't support one or the other interpretation. More research is required to answer this question.

The Cirque du Soleil story (from Nigg, 2010, p. 59-61)

In 1997, Cirque du Soleil had an injury problem with one of its touring troupes. At any time, about one quarter (25%) of its performing staff was injured and unable to perform. The typical problems were tendon insertion injuries and the affected population was primarily supporting actors who had to run and jump frequently. The jumps and runs were moderate, and the landings were not after extreme performances.

Boris Verkhovsky, the head coach of Cirque du Soleil, speculated that the stage surface might be the source of these injuries and contacted us for help. We analyzed the problem and spent three days in California where this specific group of the Cirque du Soleil was stationed at the time.

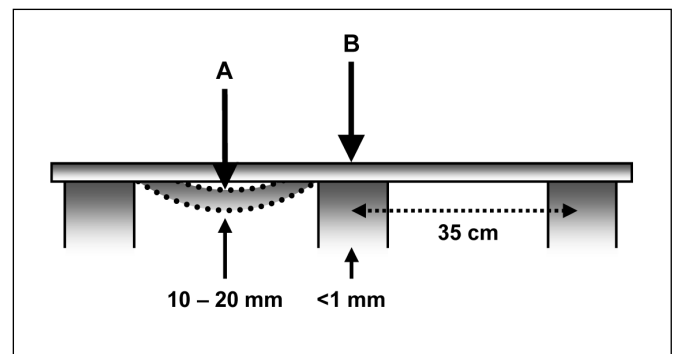


Figure 3: Schematic construction of the stage with an illustration of the possible deflection of the top surface.

The stage surface (Fig. 3) was constructed of a frame of solid and stiff beams at about 35 cm on centre. The beams were covered with a pliable material that allowed deflections of up to 2 cm when landing in the centre between the beams and deflections of less than 0.1 cm when landing on a beam.

At the time of the analysis, we had already developed our “muscle tuning paradigm.” Thus, we speculated that when the athletes/artists landed on the stage surface, they pre-activated the muscles of the soft-tissue compartments of the lower extremities (e.g., triceps surae, quadriceps, and hamstrings). The pre-activation occurs based on the athlete’s expectation about the landing condition. One major goal of pre-activation is to minimize the vibration of the soft-tissue compartments of the lower extremities. If one cannot pre-activate the muscles properly, these soft-tissue packages may oscillate substantially, since resonance effects may occur. In resonance situations, the muscle-tendon units may be exposed to high forces, which may be the reason for possible insertion problems.

Based on such considerations, we concluded that the non-uniform deflections of the stage surface produced a situation in which the artists could not prepare themselves for the landing by “tuning” their muscles to avoid excessive vibrations of the soft-tissue compartments. We proposed that the stage be changed to a much harder but uniform surface. The construction was stiffened and the new surface was uniform (but hard) over the whole stage. This way, the artists knew what to expect for the landing and could prepare (tune) their muscles accordingly. The result was that the high number of injuries quickly returned to a normal level (2 to 3%), and the artistic work continued as programmed.

Although this story provides only anecdotal evidence, in terms of the muscle tuning paradigm, it is, in our view, stunning. It would be difficult to explain the results of this story with anything other than the muscle tuning concept.

Relevance for footwear

If the muscle tuning paradigm is correct this would suggest that running shoes can influence the muscle activity before and during ground contact. High muscle activity could mean (a) increased energy used during a running cycle and/or (b) less comfort during the locomotion activity. Thus, the main effects of this paradigm would not be with respect to running injuries but rather with respect to performance and comfort.

Recently one sport shoe company decided to develop products based on the paradigm of “muscle tuning”.

Research on the topic of muscle tuning is still in its infancy. Strategies to minimize muscle tuning activities are not well understood. The most obvious approach is to change the frequency of the input signal by changing (a) the material properties of the midsole and/or (b) by changing the shape of the heel. However, there may be other approaches that have a positive effect that are not known right now.

Pronation

- Pronation: inwards rotation of the foot about its subtalar joint axis
- Supination: outwards rotation of the foot about its subtalar joint axis
- Eversion: inwards rotation of the foot about a longitudinal foot axis
- Inversion: outwards rotation of the foot about a longitudinal foot axis

The subtalar joint axis is a functional axis associated with one anatomical joint, the subtalar joint. The longitudinal foot axis is a theoretically constructed axis not associated with one specific anatomical joint. Experimentally, pronation and supination are difficult to determine (van den Bogert, Smith & Nigg, 1994). For this reason, experiments quantifying foot rotations have usually quantified eversion and inversion. For this paper the measured values discussed are always foot in- and eversion. Most studies concentrate on foot eversion, which is speculated to be a surrogate measure of foot pronation.

“Pronation” is a variable that was of interest for foot orthopaedics, podiatrists and orthotists for a long time. It was discussed long before the running boom and “excessive” pronation was typically considered as the reason for many injuries. This conceptual thinking was probably influenced by the fact that there is a movement coupling between the calcaneus and the tibia (Hicks, 1953; Hintermann, Nigg, Sommer, & Cole, 1994; Lundberg, Svensson, Bylund, Goldie, & Selvik, 1989; Nawoczenski, Cook, & Saltzman, 1995; Nigg, Cole, & Nachbauer, 1993; Stacoff et al., 2000; Wright, Desai, & Henderson, 1964). Pronation of the foot is associated with internal rotation of the tibia and it was commonly assumed that large pronation would produce a high loading condition at the knee joint.

Based on such considerations the “pronation paradigm” for running shoes was formulated (Nigg & Lüthi, 1980). It stated that *foot pronation (foot eversion) should be minimized since it is a possible reason for running related injuries.*

There are several reasons why the “pronation” paradigm should be considered with caution: (a) It is difficult to quantify “pronation”, (b) “pronation” is a natural movement and (c) many epidemiological results don’t support the paradigm.

Problems with the quantification of foot eversion/pronation

Foot eversion has been determined in many static and dynamic ways. Static measures for foot eversion include

- (a) Rearfoot angle = angle between the calcaneus and the ground (g),
- (b) Achilles tendon angle = angle between the calcaneus and the lower leg (b)
- (c) FPI-6 index = a number based on 6 different assessments of the foot (Redmond, Crosbie, & Ouvrier, 2006; Keenan, Redmond, Horton, Conaghan, & Tennant, 2007),
- (d) Navicular drop

- (e) Footprint analysis
- (f) Subjective assessment of sales people in stores
- (g) Subjective assessment of clinicians in clinics

Dynamic measures for foot eversion include

- (h) Max. Rearfoot angle (gmax),
- (i) Change of Rearfoot angle in a defined time interval (Dg10, Dgtot)
- (k) Max. Achilles tendon angle (bmax)
- (l) Change of Achilles tendon angle in a defined time interval (Db10, Dbtot)
- (m) Footprint analysis
- (n) Inertial measurement unit (IMU) algorithms

To make the situation even more complicated, measurements can be done in shoes or barefoot.

One can argue about the value of each of these variables. Some scientists suggest that the FPI-6 Index is a good assessment of pronation. Others prefer a dynamic assessment of pronation. However, a gold standard for the assessment of pronation/eversion does currently not exist. In addition, there seems to be little correlation between the different assessment variables. For instance, it has been shown (Stefanyshyn et al., 2003) that there is little correlation between subjective assessments in stores and assessments while running barefoot and/or running in shoes (Fig. 4). In the below example, of the 20 self-declared

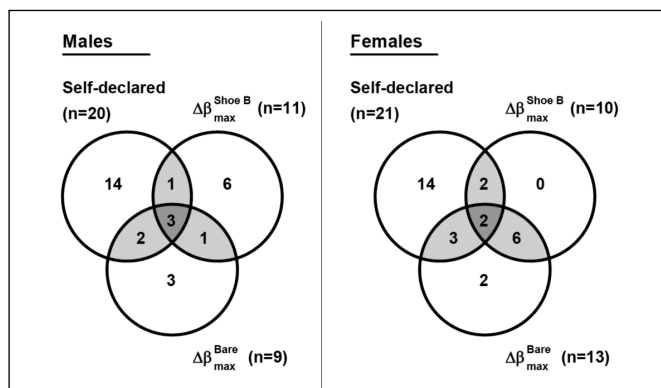


Figure 4: Venn diagram (N=34) of the relationship between “self-declared pronators”, “barefoot pronators” and “shod pronators” (from Stefanyshyn et al., 2003, with permission).

male pronators, 14 were declared pronators by a store clerk, 6 were declared pronators based on a biomechanical assessment in shoes and 3 based on a biomechanical assessment barefoot. Furthermore, an analysis of previously collected data (Nigg, Vi-
enneau, Smith, Trudeau, Mohr, & Nigg, 2017) demonstrated a lack of correlation between the Achilles tendon angle during standing and the change of the Achilles tendon angle from minimum to maximum during running for both a barefoot and a minimalist shoe condition (Fig. 5). Additionally, all other correlations between static and dynamic variables were small (all $R^2 < 0.2$). Thus, there seems to be no significant correlation

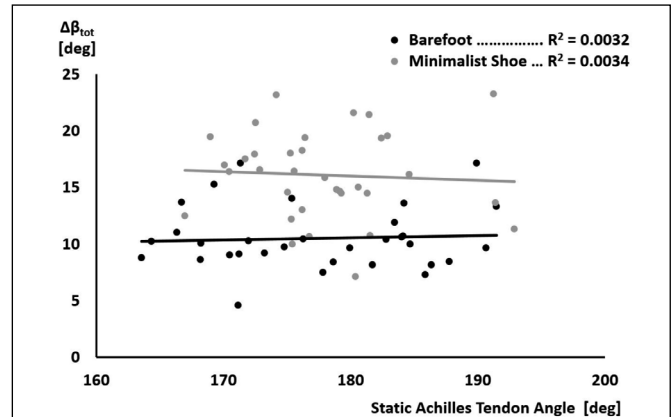


Figure 5: Correlation coefficient for a comparison between a static and a dynamic pronation variable used in the literature based on previously collected data (Nigg et al., 2017) for 34 subjects for a barefoot and a minimalist shoe condition.

between many of the used static and dynamic foot pronation/eversion variables. In other words, the variables used in most of the studies assessing “foot pronation” describe different aspects of “foot pronation” and it is unknown whether they describe foot pronation at all. Consequently, results from studies using different variables for assessing rearfoot eversion (“foot pronation”) should, conceptually, show different results with respect to type of injuries and/or injury frequencies which may or may not be related to these variables.

Natural movement and variability of runners

Another reason why the old “pronation” paradigm should be considered with caution is the fact that “pronation” is a natural movement during gait (Shorten & Mientjes, 2011). This indicates that some pronation is healthy, natural, and necessary for locomotion, and the question should focus on the optimal amount of pronation instead of trying to reduce pronation to a minimum.

The question of optimal pronation is also likely subject dependent as different subjects 1) have different ranges of pronation, and 2) have different kinematic adaptations to product interventions. An example of this was a study that investigated the occurrence of injuries in female runners, when exposed to different running shoe conditions (Ryan, Valiant, McDonald & Taunton, 2011). Regardless of foot posture type (neutral, pronated or highly pronated), one shoe type (motion control) reported the highest level of pain for runners. The investigators concluded that providing footwear interventions based on foot type, as is done in many shoe stores, may be both too simplistic and potentially cause unnecessary injuries.

Epidemiological results

Most epidemiological studies that discuss the association between “pronation” and running injuries have the same short-

coming as the epidemiological studies related to impact loading: The sample sizes are too small. However, there are two epidemiological studies that have large sample sizes, which will be discussed in the following.

The first study to be discussed in more detail (Nielsen et al., 2014) assessed foot posture of novice runners with a static measurement and grouped the 1854 feet of the 927 participants into very supinated (FPI6 < -3; N = 53), supinated (FPI6 = -3 to +1; N = 369), neutral (FPI6 +1 to +7; N = 1292), pronated (FPI6 7 to +10; N = 122) and very pronated (FPI > +10; N = 18). Their epidemiological results after a one year period of running showed significantly less injuries per 1000 km of running for the pronated group compared to the neutral group. Thus, the interpretation of this result would be that "pronation" as assessed with a static calcaneus position measure is not an injury predictor. Based on these results, one may even speculate that 'pronation' reduce the likelihood of sustaining running related injuries.

A second notable finding of this study is that excessive pronators only made up about 1% of the study participants. For this group, the injury rates were the highest, but due to the small number of over-pronators (18 out of 1854), it was not a significant result. From these results, it can be concluded that 1) pronation may be a natural and healthy component of locomotion, 2) the number of "over-pronators" is actually very small, and is likely overestimated in running shoe stores, and 3) for this 1% of the population, the excessive pronation may be a mechanism for sustaining an injury. This is in the view of the authors the first epidemiological study on foot posture type and injuries with an adequate sample size. There are two critical comments about this study: The foot posture assessment was done statically, which is, in the view of the authors, not ideal. Secondly, subjects with orthotics were excluded from the study, which may have shifted the pro-supination distribution. However, the result is nevertheless interesting and contrary to all expectations.

The second study to be discussed in more detail (Teyhen et al., 2013) analyzed the relationship between foot type and medical costs associated with lower extremity musculo-skeletal injuries in a military setting. They collected information from 668 military participants over a period of 31 months. Static foot posture was assessed using the FPI-6 index. The explicit and implicit results of this study showed (a) that the injury frequency was about the same (no significant differences) for all foot type groups with 49% for highly supinated, 55% for supinated, 48% for neutral, 51% for pronated and 51% for highly pronated feet (note, that these numbers have not been published in the paper but were calculated from information presented) and (b) that people with the highly pronated foot type (FPI-6 between +8 and +12) had significantly higher injury costs and health care utilization for injuries from the knee to the foot. The shortcomings of this study are that (a) it doesn't quantify injury frequency (even though they have the data in Table 2) but rather injury costs, (b) it doesn't deal with running but rather with a general mix of military exercises, and (c) like in the Nielsen study, the "pronation" assessment was done statically, not dynamically. In summary, there is epidemiological evidence that "pronation"

is not a good predictor of running injuries, except maybe in extreme cases (1% of population). The results demonstrate that the original pronation paradigm is likely incorrect with respect to injury development.

Conclusion

Based on these results, we have to conclude that currently, there is no variable that can be considered as the "gold standard" to quantify foot pronation. Furthermore, the idea to minimize pronation is likely misleading, as an optimal amount of pronation is a necessary component of healthy locomotion. Most importantly, there is no conclusive epidemiological or functional evidence that pronation should be a reason for the development of running injuries and that the pronation paradigm is therefore valid. The authors suggest that the pronation paradigm should not be used for discussions about the development of running injuries for the majority of the population.

Skeletal reactions to changes in footwear

One of the possible reasons that kinematic measurements do not correlate well with the incidence of injuries is that most kinematic results are affected by errors. These errors are due to the fact that kinematic data obtained through the tracking of skin-mounted markers represent the actual movement of the skin and the underlying soft tissue. To avoid these soft tissue artefacts, we did a study using bone pins in the calcaneus, the tibia and the femur with markers on them to quantify the actual skeletal movement of the lower extremities as a function of changes in footwear (Reinschmidt, van den Bogert, Murphy, Lundberg, & Nigg, 1997; Stacoff et al., 2000). The results of this study (Fig. 6) can be summarized as follows: The kinematic changes of the skeleton of the lower extremities for changes in footwear were small and not systematic.

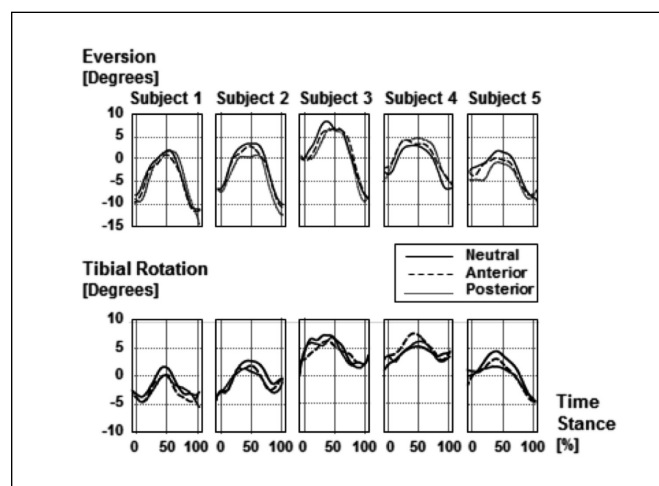


Figure 6: Effects of changes in shoe inserts on the skeletal movement (foot eversion and tibial rotation) for five subjects using bone pins while running at a slow speed. (Stacoff et al., 2000).

The preferred movement path – A new paradigm

The concept of the “preferred movement path” has been discussed before (Nigg, 2001; Nigg, 2010; Nigg et al., 2017). The development of the concept was primarily influenced by three key publications. Wilson and coworkers (Wilson, Feikes, Zavat-sky, & Bayona, 1996) proposed a “minimal resistance movement path” for the lower extremity joints based on results from cadaver experiments. Reinschmidt and colleagues (Reinschmidt et al., 1997) and Stacoff and colleagues (Stacoff, Nigg, Reinschmidt, van den Bogert, & Lundberg, 2000) showed with bone pin studies that the skeletal movement in running changes little when changing the shoe/insert conditions.

Kinematic Dogma

The findings from the bone-pin studies contradicted the traditional thinking concerning the functioning of sport shoes that shoes/inserts/orthotics should align the skeleton of the lower extremities. However, this assumption had little experimental support. Conversely, many different studies showed that the skeleton seems to change its path of movement only minimally when exposed to a change in shoe, insert, and/or orthotic (summarized in Nigg, 2010, Tab. 3.2.). One could argue that the neuromuscular system seems to be programmed to avoid deviation from this “path of least resistance.” Based on this line of thinking, one could propose that if a shoe/orthotic/insert intervention is used to produce a different skeletal movement, the locomotor system will typically activate appropriate muscles to keep the movement in a standard (preferred) path. This would be in agreement with the experimental observations that movement changes due to shoe/orthotic interventions are minimal.

Experimentally, when collecting data, one doesn't know whether a subject is in the preferred movement path or if neuromuscular adaptations are used to stay in the preferred path. The assumption is that when an intervention (e.g. shoe) supports the preferred movement path, the muscle activity is minimal. Contrary, we assume that when a shoe attempts to push the locomotor system out of the preferred movement path that muscles are activated to keep the locomotor system in the preferred movement path. Thus, in this case, the energy balance would not be optimal. These are, however, all speculations and more research is needed to support or reject these speculations. What has been found is that changing from one shoe condition to another may often not produce a change of the actual movement path. This has been documented recently (Nigg et al. 2017) in a comparison between three different shoes, a conventional running shoe (Mizuno Ryder, RY), a racing flat (Mizuno Universe, UN) and a new minimalist shoe (Mizuno BE). We determined the percentage of people not changing their ankle and knee kinematics more than 3 degrees when changing between these three shoe condition. In all three comparisons (RY-UN, RY-BE and UN-BE) and for all ankle and knee kinematic variables more than 80% of the subjects

stayed within an arbitrarily set threshold of 3 degrees. (The paper also provides information for 2 and for 5 degrees). The fact that three different shoe constructions did not change the lower extremity kinematics of the majority of individuals, seems to support the notion that people try to stay in something like a “preferred movement path” when changing shoes.

Note that the chosen (preferred) movement path is subject specific and depends on the current condition of the muscles and the locomotor control system. If a person, for instance, increases muscle strength due to strength training, the preferred movement path may change. If a person changes its training regime due to an injury, the preferred movement path may change. It may even be, that during a marathon the preferred movement path may change due to fatigue. These are all aspects that still require further investigation.

Conclusion

Based on the current knowledge and speculation we propose that the paradigm of “foot pronation” should be replaced with the paradigm of the “preferred movement path”. Running shoes and other interventions should be constructed to facilitate the runners preferred movement path with the knowledge that the preferred movement path for an individual will contain some amounts of pronation. Such shoes would be energetically advantageous, since muscle activity not related to propulsion would be minimized.

Relevance for footwear

If the preferred movement path paradigm is correct this would suggest that running shoes should influence the muscle activity before and during ground contact. High muscle activity could mean (a) increased energy used during a running cycle and/or (b) less comfort during the locomotion activity.

There is one company that attempts to build shoes based on this paradigm (Brooks) and that performs research to improve the understanding of the preferred movement path in connection with running shoes.

Currently, research related to the proposed preferred movement path is in its infancy and strategies that minimize muscle activities due to the preferred movement path are not well understood. Further research is needed to facilitate progress in this direction.

Functional groups

Different sport shoes are liked or rejected by groups of athletes. The same intervention may produce different reactions by different groups of athletes and be liked by some and disliked by others. Thus, when analysing the effects of different designs in sport shoes one will always find that the outcome depends on the subjects. The typical biomechanical conclusion is that the results are subject specific. This has to be taken into account

when analyzing sport shoe interventions and when conducting research in this area. The idea of “functional groups” should help in these situations and will be discussed in the next few paragraphs.

Definition

A functional group in sport shoe research is a group of subjects that reacts to a specific shoe/orthotic/insert intervention in a similar way.

Reactions to Interventions

When exposing a person to a shoe/orthotic/insert intervention, different groups of subjects react differently (Nigg, Stergiou, Cole, Stefanyshyn, Mündermann, & Humble, 2003). For instance, when using a medial support, some runners shift the center of pressure medially, some move it laterally and some don't change the location of the center of pressure at all (Fig. 7). Such interventions, however, influence the loading in the knee joint (Fig. 8) with substantial increases or decreases of the knee joint moments. If, for instance an orthotist prescribes and fabricates an orthotic, he/she may not know what the effect on a specific patient is and they may produce an outcome that may not be desired (e.g. high knee moments/loading). The same is true for the selection of a running shoe and the same is true when looking at all kinds of variables (muscle activity, kinetics, kinematics, pressure, etc.).

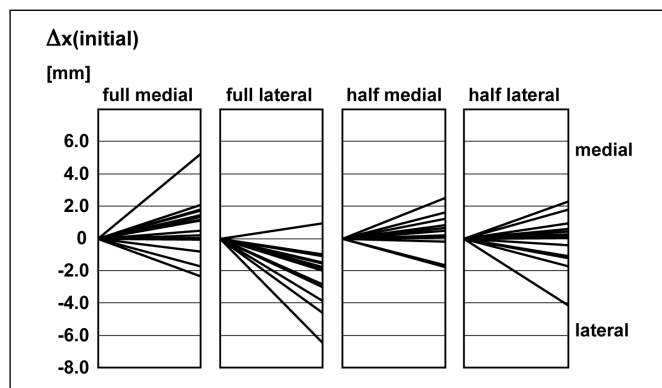


Figure 7: Mediolateral shift, Δx , of the centre of pressure (COP) path during the initial stance phase due to intervention with full medial, full lateral, half medial, and half lateral shoe inserts. (Nigg et al., 2003). Changes are with respect to the neutral insert condition. A positive result indicates a shift toward the medial side, a negative result indicates a shift toward the lateral side.

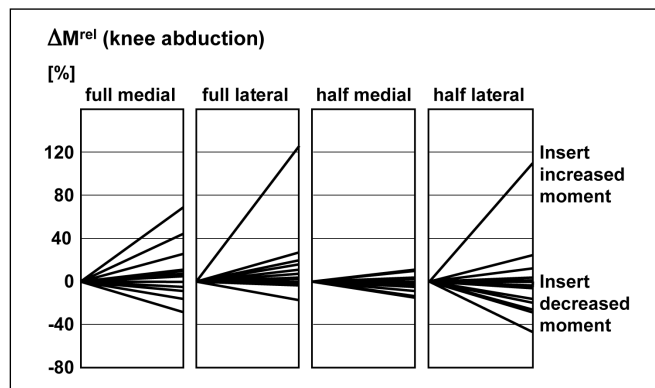


Figure 8: Relative changes in maximal knee abduction moments due to intervention with full medial, full lateral, half medial, and half lateral shoe inserts. (Nigg et al., 2003).

Identification of functional groups

Currently, there are many different construction features known for sport shoes (e.g. soft vs. hard midsoles; wide vs. narrow shoe lasts etc.). Additionally, there are many different characteristics known for subjects (e.g. high vs. low arch; flexible vs. stiff foot etc.). However, the connection between these two groups of characteristics is not well understood. Consequently, one has problems to determine the “right shoe” for a given athlete.

It is suggested that research on sport shoes should concentrate on identifying functional groups. From a theoretical point of view, all measured data should be vectorized (Nigg, 2010). In vector representation, the measured data for each trial/subject are represented by one point in a high dimensional vector space. This high dimensional vector space is populated by the mean movement patterns of these individuals, where ‘movement pattern’ includes many different variables. It is likely that groups of subjects who behave in a functionally similar way would be grouped/clustered in this vector space.

Thus, one is interested in methods that can be used to identify such clusters of subjects with similar characteristics. Powerful approaches for analyzing data in vector space include (a) principle component analysis, and (b) various types of classification methods such as support vector machines. Both methods are excellent tools to extract information from signals in cases where the key elements are not yet known and the contributing components are multifactorial.

For example, we performed a vector-based analysis of lower extremity kinematics during running from 88 male and female subjects with varying ages (Hoerzer, van Tscherner, Jacob, & Nigg, 2015). The time-dependent kinematic data were vectorized and clustered using an unsupervised learning algorithm (i.e. self-organizing maps) and support vector machines to identify groups of subjects with distinctive movement patterns. Eight groups with group-specific movement patterns were detected. While some of the groups differed in age and sex, other groups had similar age and sex distributions but differed in their subjective comfort ratings with respect to three

shoes with a different midsole hardness. This result shows that vector-based analyses can be useful in detecting groups of individuals with similar movement patterns but different responses to certain running shoe characteristics.

While these approaches are ideal for research projects, they are too complicated for a quick in store assessment. Consequently, a second group of research projects should be started to find simple methods for identifying functional groups in a sport shoe store. Correct selection of sport shoes will only be possible when such solutions are provided.

Conclusion

The experimental data supports that specific groups of individuals react differently to footwear related interventions. As a result, research that attempts to find the appropriate shoe for a runner should focus on groups of individual runners that behave similarly (functional groups) to a shoe intervention. The concept of functional groups is, therefore, a strategy for research to connect the characteristics of shoes with the characteristics of subjects and when combined with advanced analytics, can become a powerful tool for matching consumers with the appropriate products.

Final comments

This paper suggests several changes in our thinking about running shoes, running injuries and running performance. Specifically, this paper suggests:

1. The commonly used paradigm concerning the association between running injuries and impact loading does not have functional and/or epidemiological support. Unless large, prospective studies provide evidence for a relationship between impact loading and running injuries, the paradigm should be dismissed.
2. The commonly used paradigm concerning the association between running injuries and foot pronation does not have functional and/or epidemiological support and should be dismissed.
3. It has been proposed that impact loading is important because of soft tissue vibration and the corresponding muscle tuning. This new paradigm of muscle tuning may be related to injuries, performance and/or comfort. The experimental evidence for this new paradigm is, however, still weak and needs further research.
4. It has been proposed that foot kinematics are important because of the preferred movement path paradigm. This new paradigm does not seem to be related to running injuries but rather to performance and/or comfort. The experimental evidence for this new paradigm is, however, still weak and needs further research.
5. Different runners react to footwear interventions differently. Groups of runners that react in a similar way are called functional groups. These functional groups are extremely

important when research is performed to analyse running related questions.

Participants

Second-level subheadings should be indicated in italics (without a blank line after the subheading as "Participants" before this paragraph). In cases of articles presenting original research, the following second-level subheadings would be preferred: Participants, Apparatus, Procedure, Measures (or similar). If more than a single experiment is reported, these subheadings should appear on the third level as follows.

This is a third-level subheading. Third-level subheading should be indicated in italics (as "This is a third-level subheading" at the beginning of this paragraph (without a blank line before the subheading and also without a return after the subheading). Please use third-level subheadings as sparsely as possible. Refrain from using fourth-level subheadings.

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Competing Interests

The authors have worked over about 40 years with more than 40 industry partners. Many of these contacts were paid for by these partners. Results and understanding from projects with these partners have influenced the development of the paradigms, presented in this paper. However, the authors declare that no competing interests exist.

Data Availability Statement

All relevant data are within the paper.

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New Hypotheses and Unanswered Questions in Running Injury Research – comment on Nigg et al.

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ABSTRACT

After critical evaluation of the evidence, Nigg et al.'s target article reject currently discussed hypotheses regarding relationships between impact forces, pronation, and running injuries. In doing so, they highlight methodological questions underlying research in this field. This commentary focuses on three such questions including: how are impact forces and the relationship between impact and injury being quantified, what are the methods currently used to measure foot pronation and what are metrics being extracted, and the importance of focusing on individual response patterns. Each of these areas represents important venues for continued development in the field of running biomechanics and running injuries.

Keywords:

Impact forces – frequency analysis – pronation – single subject analysis

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Introduction

The target article by Nigg et al. (2017) challenges decades of research regarding whether impact forces or excessive pronation are related to running injuries. Instead they propose two new paradigms: muscle tuning and the preferred movement path. In discussing the implications of these concepts, the authors emphasize how individuals can respond differently to a given intervention and thus recommend the need to focus on functional groups who respond similarly. Underlying the development of the paradigms proposed by Nigg et al. (2017) are questions regarding consistency or inconsistencies in the methodologies and approaches currently used in running biomechanics research. This commentary will consider each of these areas while posing questions for the running research community to consider in future research.

Impact Forces

Nigg et al. (2017) conclude there is little evidence supporting the relationship between impact forces and running injuries and, as an alternative, propose the hypothesis of muscle tuning. There is preliminary evidence suggesting that muscle tuning happens during running (Boyer & Nigg, 2006, 2004), and this hypothesis should be further investigated, especially in prospective studies related to injury development. However, one could also ask if the reason epidemiologic studies have not shown a clear link between impact forces and running injuries is that the epidemiologic studies have not actually been measuring true impact forces. Spectral analysis of ground reaction forces during running reveals that the classic “impact peak” results from the superposition of high frequency content from the impact between the foot and the ground and low fre-

quency content representing the movement of the rest of the body mass (Shorten & Mientjes, 2011). These high frequency impact components are present in the ground reaction force signal even when an "impact peak" may not be discernable in the time domain (Gruber, Davis, & Hamill, 2011; Gruber, Edwards, Hamill, Derrick, & Boyer, 2015). Thus, only analyzing the "impact peak" in the time domain can lead to erroneous conclusions. For example, Shorten and Mientjes (2011) showed that when comparing shoes with three different levels of cushioning, a time domain analysis of the "impact peak" suggested the softest shoe had the highest "impact peak". In contrast, the frequency domain analysis revealed the high frequency impact components were attenuated in the softest shoe. However, because they occurred later in stance, they were summed with more low frequency content and thus, the higher "impact peak" in the time domain. Without analyzing the true impact components one might have mistakenly concluded the soft shoe increased impact forces.

While several prospective studies evaluating relationships between impact forces and injury have been conducted (Bredeweg, Buist, & Kluitenberg, 2013; Davis, Bowser, & Mullineaux, 2016; Messier et al., 2016) these studies have all examined the "impact peak" or loading rates in the time domain. Considering the discrepancies between analyzing impact forces in the time and frequency domains, one could question whether these studies actually reveal information about the relationship between impacts and running injuries, and by extension, should we reject the association between impacts and running injuries, as advocated in the target article? Or, is it more accurate to say that we really don't know whether there is a relationship as, to date, no prospective studies on running injuries and impact forces have actually quantified impacts and instead focused on the time domain measures of "impact peak" or loading rates?

Pronation

As with impact forces, Nigg et al. (2017) systematically critique the evidence linking "excessive" pronation with running injuries and conclude there is not enough evidence to support the relationship. However, one needs to ask whether this lack of relationship is due to one not existing, or due to the methods currently being used in the literature for measuring this parameter. Pronation is a complex movement involving motion in multiple planes at multiple joints and the movement of the individual joints involved is difficult to measure. Some authors have attempted to account for this complexity by calculating ankle movement about an anatomical subtalar joint axis (O'Connor & Hamill, 2005) or summing motion about multiple axes to calculate three dimensional pronation (Willems, Witvrouw, De Cock, & De Clercq, 2007). However, most running studies place three markers on the shoe heel counter and calculate rearfoot eversion about the long axis of the foot as a surrogate measure of pronation. Should this continue to be acceptable or should

more anatomically relevant measures of joint motion be encouraged?

Additionally, there are several other questions which should be addressed before rejecting the hypothesis that abnormal pronation may be related to running injuries. For example, what constitutes "excessive" pronation? There is no consensus definition. Is there a relationship between amounts of pronation and tissue loading? Musculoskeletal modeling has provided insights into numerous running injuries including iliotibial band syndrome (Hamill, Miller, Noehren, & Davis, 2008), patellofemoral pain syndrome (Besier, Fredericson, Gold, Beaupre, & Delp, 2009), and tibial, femoral, and metatarsal stress fractures (Edwards, Gillette, Thomas, & Derrick, 2008; Edwards, Taylor, Rudolph, Gillette, & Derrick, 2009; Firminger, Fung, Loundagin, & Edwards, 2017). These same strategies could be brought to bear on the question of whether the amount of pronation is related to tissue loading. What about alternative hypotheses such as the amount of pronation used as a function of total joint range of motion available (Rodrigues, TenBroek, & Hamill, 2013) or the duration of pronation instead of the amount (Becker, James, Wayner, Osternig, & Chou, 2017). While the preferred movement path concept should continue to be developed, these other questions are examples of areas which should be examined in greater depth before rejecting the hypothesis that abnormal pronation may be related to muscle injury.

Functional Groups

Nigg et al. (2017) conclude the target article by presenting the concept of functional groups, which they define as a group of subjects that reacts the same way to some type of intervention. The concept of studying each individual and how they respond to a given intervention is not new in biomechanics literature. In a series of studies from the 1990s Bates and colleagues demonstrated how individualized, subject specific responses could be observed when evaluating impact forces while running with different shoes (Bates, Osternig, & Sawhill, 1983; Dufek & Bates, 1991; Dufek, Bates, Stergiou, & James, 1995) or when landing from drop jumps (Caster & Bates, 1995; Dufek et al., 1995; Schot, Bates, & Dufek, 1994). As such, Bates advocated for using single subject analyses, saying that no two individuals are identical and, when one considers the plasticity of the neuromuscular system, we have an almost infinite number of degrees of freedom which can be used to control any given action (Bates, 1996). Such individualized responses are highlighted by Nigg et al. (2017) with the example of how the same heel wedges can result in different changes in the center of pressure trajectories and corresponding knee abduction moments across subjects.

While Bates and colleagues have presented several innovative methods for single subject data analysis (Bates, 1996; Bates, Dufek, & Davis, 1992) these approaches still present challenges, especially when it comes to generalizing results to larger populations (Reboussin & Moran, 1996). In this regard, the approach

suggested in the target article by Nigg et al. (2017) represents a potentially powerful shift in research design in biomechanics studies. Their recommendation to vectorize the data and use analysis techniques such as principal component analysis or classification algorithms such as support vector machines for detecting group differences provides a powerful tool for identifying functional groups while conceptually recognizing that individualized response patterns likely exist. To date, while such approaches have not been used with high frequency, they have demonstrated the ability to distinguish specific kinematics between groups of runners (Foch & Milner, 2014; Phinyomark, Hettinga, Osis, & Ferber, 2015). It seems logical that such approaches will only grow in popularity in the coming years and provide new insights into relationships between running mechanics and injury.

Conclusion

The hypotheses presented by Nigg et al. (2017) in their target paper are valuable additions to the running biomechanics field. While they require further study and validation the process of doing so will force the field to also reconsider long held beliefs and commonly used methodologies. Perhaps the combination of these efforts might start finally making a positive dent in the incidence and nature of running injuries.

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All relevant data are within the paper.

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Running impact forces: from half a leg to holistic understanding – comment on Nigg et al.

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ABSTRACT

Running impact forces have immediate relevance for the muscle tuning paradigm proposed here and broader relevance for overuse injuries, shoe design and running performance. Here, we consider their mechanical basis. Several studies demonstrate that the vertical ground reaction force-time (vGRFT) impulse, from touchdown to toe-off, corresponds to the instantaneous accelerations of the body's entire mass (M_b) divided into two or more portions. The simplest, a two-mass partitioning of the body (lower-limb, $M_1=0.08 \cdot M_b$; remaining mass, $M_2=0.92 \cdot M_b$) can account for the full vGRFT waveform under virtually all constant-speed, level-running conditions. Model validation data indicate that: 1) the non-contacting mass, M_2 , often accounts for one-third or more of the early "impact" portion of the vGRFT, and 2) extracting a valid impact impulse from measured force waveforms requires only lower-limb motion data and the fixed body mass fraction of 0.08 for M_1 .

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Two-mass model – effective mass – ground reaction forces – running performance – spring-mass model

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Impact Forces Revisited

Dr. Nigg and colleagues deserve commendation for efforts that have endowed the area of running biomechanics with a sizeable body of empirical observations. These observations have, and undoubtedly will, continue to inform work on a broad range of topics that include running injuries, running shoes and the relationship between the two. Their willingness to confront the experimental challenges involved in studying a largely unpredictable phenomenon like running injuries deserves particular praise.

Here, we focus on the impact force conclusions offered by Nigg, Mohr and Nigg (2017) in their target article. While their contribution purports a lack of importance in overuse injury etiology, there are compelling scientific reasons to consider

their basis and importance from an independent, contemporary perspective. These are: 1) the existence of credible evidence supporting a running impact force-overuse injury link (Daoud, Geissler, Wang, Saretsky, Daoud, & Liebermann, 2012; Milner, Ferber, Pollard, Hamill, & Davis, 2006), 2) the direct effect of impact forces on bodily motion and performance (Clark & Weyand, 2014), and 3) the need for valid quantification to advance general understanding and inform specific applications. One noteworthy application is the input signal required by the muscle-tuning paradigm Nigg *et al.* advance in their target article here. More broadly, the inability to quantify running impact forces recently noted by Nigg and colleagues elsewhere (Baltich, Maurer & Nigg, 2015) is obviously a direct impediment to reaching firm conclusions regarding their importance.

From our perspective, the development of a quantitative understanding has been at least partially impeded by two assumptions that have framed the study of running impact forces for decades. These are: 1) assuming that the early portion of the vertical ground reaction force-time waveform can be attributed to a small fraction (i.e. an “effective mass”) of the body’s total mass (M_b) while ignoring the rest (Chi & Schmitt, 2005; Denoth, 1986; Derrick, 2004; Lieberman, Venkadesan, Werbel, Daoud, D’Andrea, Davis, Mang’eni & Pitsilades, 2010; Nigg, 2010; Nigg, Mohr, Nigg, 2017), and 2) assuming that the impact impulse can be quantified using the localized force peak often visible on the rising edge of the measured waveform (Figure 1). Three studies indicate that these assumptions obscure the mechanics of the impact event.

The first study was provided by Bobbert, Schamhardt and Nigg (1991) more than 25 years ago. These investigators demonstrated that the instantaneous accelerations of seven body mass components (comprising 100% of M_b : right and left foot, shank, and upper leg components plus a combined head-arms-torso mass) acquired from motion data, can be summed to provide a close match to the measured total vertical ground reaction force-time (vGRFT) waveform during slow and moderate speed running (i.e. $F_{z1} + F_{z2} + F_{z3} + F_{z4} + F_{z5} + F_{z6} + F_{z7} = F_{z\text{-total}}$; where z designates the vertical component of the ground reaction force). This noteworthy experimental accomplishment was based on Newton’s 2nd Law including the first-principle recognition that the measured vGRFT waveform must somehow correspond to the instantaneous accelerations of 100% of the body’s mass. The second insightful study was the detailed temporal and spatial analysis of the rising edge of the vGRFT undertaken by Shorten and Mientjes (2011). From pressure mapping data on the sole of the foot and frequency analyses of measured waveforms, these investigators also concluded that the body’s entire mass contributed to the rising edge of the waveform. Per their title, they concluded that the localized, rising-edge waveform force peak widely attributed to heel impact, is in fact, “neither heel, nor impact” during heel-toe running.

The most recent of the three studies involved an experimental effort from our laboratory (Clark, Ryan & Weyand, 2017) that, like Bobbert *et al.* adopted a Newtonian approach. We did so with the goal of identifying the simplest partitioning of the body that might account for the vGRFT waveform in full. Our efforts led to the two body-mass component, two-impulse waveform explanation illustrated in Figure 1. Ultimately, this approach was able to predict 500 measured vGRFT waveforms acquired at speeds from 3.0 to 11.0 m/s regardless of the runner’s foot-strike mechanics. Due to the model’s conciseness, only three inputs are required to generate the waveforms from a runner’s gait mechanics: contact time, aerial time, and the vertical acceleration of the lower limb. The close agreement between model-generated and measured vGRFT waveforms ($R^2=0.95$) supports the general validity of the two-mass, two-impulse explanation for their mechanical basis.

The Rising Edge of the vGRFT Waveform: Impact Is Not Enough

Clearly, additional experimental work remains to test and refine the existing Newtonian explanations for running vGRFT waveforms. However, the two studies that have successfully linked bodily motion to running ground reaction forces share the foundational recognition that the waveform represents the summed acceleration of 100% of body mass.

The holistic Newtonian view that emerges for the rising-edge of the total vGRFT waveform, broadly conceived elsewhere as an “impact-only” event, is illustrated in Figure 1. The data appearing in the figure have been adapted from original vGRFT data acquired at a speed of 5.0 meters per second from a runner with heel-strike mechanics. As illustrated, the body’s full mass contributes to the rising edge of the waveform. Accurately predicting the magnitude and timing of the localized peak, for example, requires summing the impulse contributions of the model’s body mass components. Per the illustration, correct prediction of the overall impact mechanics using the two masses in our model relies heavily on the kinematic data used to determine Δt_1 from the period elapsing between the instant of initial foot-ground contact and subsequent time at which mass M_1 slows to a vertical velocity of zero. Correct identification of the localized rising-edge peaks for heel-strikers at all speeds and competitive sprinters at faster ones as previously reported would have been virtually impossible (Clark, Ryan & Weyand, 2017, Figures 5, 6 and 7) without both: 1) accurate

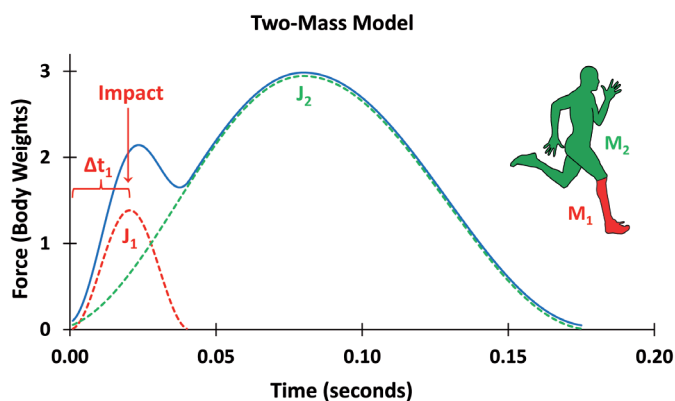


Figure 1: Running vertical ground reaction forces can be quantified as the sum of two impulses: a relatively brief impact impulse (J_1) that corresponds to the deceleration of the foot and shank ($M_1=0.08 \cdot M_b$), and a larger, longer-duration impulse (J_2) that corresponds to the acceleration of the remainder of the body’s mass ($M_2=0.92 \cdot M_b$) throughout the stance period. Both impulses begin at the instant of touchdown and contribute substantially to the rising-edge of the force-time waveform. Note that impact impulse, J_1 , is quantified from 8% of M_b and the time Δt_1 at which the ankle reaches its minimum vertical position.

kinematic data, and 2) a model capable of predicting the significant variability in the timing and magnitude of rising-edge force peaks across scores of different footfalls.

Figure 1 also reveals the specific manner in which the assumptions required by the effective mass techniques obscure the mechanical basis of the rising edge of the waveform. In the footfall illustrated, the effective mass approach assumes that mass M_2 would make little or no contribution to the rising-edge impulse up to the localized force peak. However, as illustrated, M_2 is actually responsible for roughly one-third of the total impulse over this early period of this illustrated waveform. During slow and moderate speed fore-foot strikes, the impulse contributions of mass M_2 actually exceed those of M_1 , primarily because the impact period Δt_1 is relatively longer (Clark, Ryan & Weyand, 2017, Figures 5 and 6, Table 2). Also evident in the figure is that the localized peak on the total vGRFT waveform is not simultaneous with the peak of impact impulse J_1 as implicitly assumed by effective mass quantification techniques. Rather, the time-dependent contributions of impulse J_2 cause the total waveform peak to occur at a later point in time than the J_1 impulse peak. In the case of most forefoot strike waveforms, the longer Δt_1 period results in the rising edge of the measured waveform lacking a localized force peak altogether (Clark, Ryan & Weyand, 2014; Clark, Ryan & Weyand, 2017, Figure 6, Table 2).

Impact Forces and New Paradigms: Retro- and Prospective Considerations

Intuitive appeal and computational simplicity may be responsible for the common conceptualization and quantification of the rising edge of human running vGRFT waveforms as an impact-only phenomenon. However, the works synthesized here: 1) provide a valid mechanical basis for the vGRFTs waveforms based on the body's entire mass, and 2) offer quantitative methods that apply over essentially all level-speed and foot-strike conditions. A two-mass partitioning of the human body allows the full running vGRFT waveform to be predicted from gait motion. The two-mass approach also allows the impact portion of the impulse to be extracted from measured vGRFT waveforms. Doing so requires only motion data from the ankle and the fixed lower-limb mass fraction identified for M_1 . Finally, we applaud Nigg, Mohr and Nigg for proposing muscle tuning and movement path paradigms in an effort to advance basic and applied understanding of running mechanics. We share their view that evaluating these paradigms will be a major and lengthy experimental undertaking. One useful tool for these efforts, directly in the case of muscle tuning and indirectly for preferred movement paths, is the holistic quantitative understanding of impact forces that is currently available.

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Competing Interests

The authors declare competing financial interests. Peter Weyand, Laurence Ryan and Kenneth Clark are the inventors of US Patent #8363891 which is owned by SMU and contains scientific content related to that presented in the manuscript. The patent is licensed to SoleForce LLC in which the three aforementioned individuals are equity partners.

Data Availability Statement

All relevant data are within the paper.

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A discussion of the Muscle Tuning and the Preferred Movement Path concepts – comment on Nigg et al.

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ABSTRACT

Nigg and colleagues propose two new paradigms, the Muscle Tuning and the Preferred Movement Path concepts. The purpose of this commentary is to discuss plausibility and challenges of these two concepts. Both concepts are highly plausible from a mechanical point of view and they also go in line with every-day observations. The main challenges for the muscle tuning paradigm are that (a) this mechanism is only one of several mechanisms in how the body adapts to impacts, and (b) it is very difficult to develop testable predictions from this paradigm since the mechanical (vibrational) properties of the leg are highly subject-specific and complex. The main open questions regarding the preferred movement path paradigm relate to (a) its integration with the concepts for movement variability, and (b) to the circumstances under which the preferred movement path might change.

Keywords:

Human Movement – Adaptation to Impact – Movement variability – Kinematic Analysis – Principal Component Analysis PCA

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Two paradigm shifts are outlined in the target article of Nigg and colleagues published recently in CISS (Nigg, Mohr, & Nigg, 2017) and also in some previous publications (Nigg, 2001, 2010; Nigg, Baltich, Hoerzer, & Enders, 2015; Nigg et al., 2017). The first proposed paradigm shift suggests that the impact forces occurring as the foot strikes the ground during running should not be regarded as a major cause for running related injuries. While this suggestion at first glance seems counter-intuitive, the authors present functional considerations as well as epidemiological observations to substantiate this conclusion. Similarly, the paradigm that foot pronation is a potential cause for running injuries is challenged by conceptual considerations as well as an apparent lack of epidemiological support. Instead, the authors propose two other biomechanical mechanisms which, in their opinion, are more relevant in the context of running and running-related injuries: the “muscle tuning” and the

“preferred movement path” concepts. The current commentary will discuss these two concepts from a critical perspective.

Muscle tuning

The underlying idea for the muscle tuning concept is that mechanical systems of hard and soft materials (bone and soft tissues in the leg), when exposed to impacts (such as the heel strike on the ground in running), are expected to exhibit vibrations. In fact, when watching the calf or other muscle groups of the leg during heel-toe running, one can observe a shockwave travelling through these soft tissue compartments. However, these shockwaves usually do not trigger significant vibrations. The muscle tuning concept proposed by Benno Nigg suggests that the neuromuscular system actively adapts (“tunes”) the

mechanical properties of the leg in such a way that vibrations are critically damped.

From mechanical, motor learning, or evolutionary perspectives this concept is highly plausible: When the neuromuscular system is expecting an impact, such as a heel strike in running or a jump landing, then fewer vibrations are observed in the biomechanical systems than one would expect in similar passive mechanical systems. When the system is not expecting the impact, e.g. an unexpected step when ascending or descending a stair, then much larger shockwaves and vibrations can be observed. It makes sense that an adaptation to minimize vibrations in a movement is part of the motor learning process when acquiring that movement. Additionally, considering that internal vibrations within the biomechanical system would excessively strain particularly the structures that link soft and hard tissues, it also makes sense that the skill and the physiological prerequisites for such an adaptation mechanism have developed evolutionarily.

However, there are at least two criticisms that can be brought forward. First, muscle tuning is not the only mechanism playing a role when the biomechanical system prepares for impact. Particularly the tendons play an important role, for example, in order to exploit the stretch-shortening cycle (Komi, 2000; Nicol, Avela, & Komi, 2006) or simply to absorb and then dissipate impact energy (Roberts & Konow, 2013). Both of these mechanisms require pre-activation of the muscles. During impacts it is also common to observe muscular co-contraction in order to stabilize the joints (Hirokawa, Solomonow, Luo, Lu, & D'ambrosia, 1991). Hence, in actual movements "muscle tuning" most likely takes the form of a modulation of muscular pre-activation, co-contraction or movement-related activation; it is most likely not an activation that can be observed or studied independently.

Second, the vibrational properties of a system depend on the material and geometric properties of that system. However, it is impossible to correctly model the actual (and constantly changing) mechanical and geometrical properties of the leg during a movement, and hence, it seems largely impossible to make anything but rough estimates about its vibrational properties. Consequently, the muscle tuning principle can serve as one of the reasons for high variability and high subject-specificity in impact responses (Huber et al., 2013), but future hypothesis-driven research is significantly hampered by the difficulty in developing precise predictions.

Preferred movement path

The preferred movement path paradigm is usually introduced from a perspective of orthotic intervention aiming at changing skeletal alignment (Nigg et al., 2017; Nigg, 2010; Nigg et al., 2017). Ample research by Benno Nigg and many other colleagues found that such interventions usually fail to produce significant changes in the joint kinematics (Nigg, 2010). Instead, it seems that the neuromuscular system prefers a spe-

cific, individual kinematic pattern, called the "preferred movement path". When external interventions interfere with this "path", the neuromuscular system counteracts, e.g. with modified muscle activation, such that the original movement pattern is preserved.

As such, the preferred movement path paradigm represents a compelling synthesis of conclusions from many empirical studies. It is also a common every-day observation that human gait has a specific, highly individual pattern to it – sometimes we can identify a person only from observing their gait characteristics. However, a number of open questions and also some discrepancies in the definition of what the preferred movement path exactly is, remain. One unresolved issue is how the preferred movement path concepts can be integrated with another important concept in human movement science, the concept of movement variability. We know from Bernstein (Bernstein, 1966), Latash (Latash, 2000) and many others (Bartlett, Wheat, & Robins, 2007) that variability is inherent to human movement. In gait, no step is exactly equal to any previous step. Is it then possible that there is one single trajectory that the neuromuscular system is trying to perform? – One solution to this question might be that the preferred movement path should really be interpreted as a "path" of similar trajectories, rather than as one single trajectory. Similar to the concepts of uncontrolled manifold hypothesis (Latash, Scholz, & Schönner, 2002) or minimal intervention principle (Todorov & Jordan, 2002, 2003) we could speculate, that the sensorimotor system allows variability as long as the trajectories remain within the preferred movement path, but starts to actively intervene when too large deviations are detected.

Another open question is whether the preferred movement path can change. In their target article Nigg and colleagues suggest that training, injury or fatigue may affect the preferred movement path. In our opinion, long term adaptations seem plausible, for example, a recent study found differences in movement patterns between high-mileage and low-mileage runners (Boyer, Freedman Silvernail, & Hamill, 2014), which suggest that an adaptation in the preferred movement path seems likely. Short-term adaptations, however, seem less plausible, especially if the preferred movement path is based on a skeletal "minimal resistance path" (Wilson, Feikes, Zavatsky, Bayona, & O'Connor, 1996). If anatomical properties shape the preferred movement path, then it seems rather unlikely that it would change due to fatigue or other short term effects. To be precise, fatigue can change running kinematics (Chan-Roper, Hunter, Myrer, Eggett, & Seeley, 2012). However, if the preferred movement path is defined as a theoretical optimum movement pattern, then such kinematic changes due to fatigue are only a sign that the neuromuscular system is no longer able to perform close to its theoretical optimum. The observation that novice runners show greater changes with fatigue than experienced runners (Maas, De Bie, Vanfleteren, Hoogkamer, & Vanwanseele, 2017) could be a sign that experienced runners have developed better strategies allowing them to perform close to the preferred movement path despite fatigue.

Most studies investigating the preferred movement path focus on individual joint angles, e.g. at the ankle or knee (Nigg et al., 2017). However, within the biomechanical system in a specific movement (running), these angles cannot change independently from each other (Federolf, Boyer, & Andriacchi, 2013). For future research into the preferred movement path we would argue that methods that study the coordination of segment movements, such as principal component analysis PCA (Federolf, Reid, Gilgien, Haugen, & Smith, 2014; Federolf, 2016; Gløersen, Myklebust, Hallén, & Federolf, 2018) should be applied. One reason is that PCA-based analyses tend to be more sensitive compared to many other methods, for example, while Boyer and colleagues found differences in coordination patterns between experienced and non-experienced runners (Boyer et al., 2014), other studies employing different methods did not (Floria, Sanchez-Sixto, Ferber, & Harrison, 2018).

Résumé

The current comment on the muscle tuning and preferred movement path concepts may appear to focus on challenges, unclear aspects or discrepancies in these concepts. This is not meant as a challenge to these concepts, which, in our opinion, are plausible and convincing. Rather, the current comment is meant as an outline for future work that should be done.

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A paradigm shift is necessary to relate running injury risk and footwear design – comment on Nigg et al.

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ABSTRACT

In this commentary, we respond to suggestions that new paradigms are needed to relate running-related injury risk and footwear design. We concur with the authors of this paper that the previous paradigms on which footwear were designed are faulty. We also concur with the authors that new paradigms are indeed needed and that research must take into consideration more epidemiological studies and more prospective biomechanical studies. The authors suggest new paradigms including muscle tuning, the preferred movement path and functional groups. However, we do raise questions about each of these suggestions regarding how these paradigms can be developed in future research designs.

Keywords:

injury risk – ground reaction forces – pronation – muscle tuning – preferred motion path

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Introduction

The popularity of running as a form of physical activity began in the 1970's instigating the development of sports shoes designed from a biomechanical perspective. At this time, the biomechanical considerations of running footwear focused on two guiding principles: 1) decreasing the risk of running related injuries; and 2) improving performance. For the most part, the former has taken precedence over the latter. There has been two injury-related foci that have been studied extensively: 1) cushioning the shoe during foot/ground collisions; and 2) controlling rearfoot calcaneal eversion/pronation. However, despite advancements in research and subsequent improvements in running footwear design over the years, the rates of running-related injuries have not decreased (Taunton et al., 2002). While footwear is an injury risk factor, it must be considered along with several other risk factors. Overall, there

certainly is a need for new paradigms to form the basis for footwear design.

Reducing the Load During the Foot/ Ground Collision

The relationship between impact forces and injury was derived initially from animal studies in which joints were subjected to numerous repeated impacts (Radin & Paul, 1971). In this study, bovine joints were significantly degraded suggesting that the repeated impacts were deleterious and a risk factor for injury. However, several studies have provided evidence suggesting that high impact loading is not necessarily linked to running injuries. Such studies have reported that knee osteoarthritis is found in equal frequency in runners and non-runners (e.g. Lane et al., 1986). Nigg (2001) reported that runners with a higher

injury frequency actually had lower maximum vertical impact force and loading rate than those who had higher values of these parameters. Thus, it appears that, unlike previous thinking, neither high impact peaks nor high loading rates relate directly to injury. As these authors note, the use of ground reaction forces (GRF) (i.e. initial vertical peak and vertical loading rate) is not the most appropriate method for evaluating impact load. However, in the biomechanics literature, there are still a number of studies supporting a relationship between higher vertical GRF parameters and injury (e.g. Milner et al., 2006).

Rearfoot Pronation/Calcaneal Eversion

Possibly the most misleading concept in footwear design is the pronation paradigm. Pronation (or its surrogate, calcaneal eversion) is a natural foot motion. This natural motion has been proposed to be related to the preponderance of knee injuries by the linkage of calcaneal eversion, tibial internal rotation and knee flexion. It has been suggested that if there is excessive calcaneal eversion or calcaneal eversion occurs late in the stance phase, greater stress would be placed on the knee joint with tibial internal rotation lasting well into the knee extension phase of support. The term 'excessive-' or 'over-pronation' thus was thought to be a risk factor for injury and footwear manufacturers created footwear to reduce or minimize pronation. However, there is no clinical definition for 'normal' pronation so it is difficult to determine what is excessive. Thus, the cause of 'pronation like' injuries is speculative at best. Possibly evaluating eversion using a 'pronation buffer' paradigm (Rodrigues et al., 2015) may shed more light on the use of eversion as a design feature in footwear.

As Nigg and associates (2017) point out, there are a number of methodological considerations that must be considered in measuring pronation. First, markers placed on the shoe do not reflect the movement of the foot, presenting a critical measurement issue. Next, pronation should be measured about the sub-talar joint axis that is an oblique axis and results in pronation being very difficult to measure. The surrogate measure commonly used for pronation is calcaneal eversion that is commonly determined as a rotation about the long axis of the foot. Lastly, the inter-subject variability is extremely large. Thus, the parameters derived from the calcaneal eversion angle have not been strongly correlated with injury risk (e.g. Nielsen et al., 2014).

Solution to Footwear Design

Muscle Tuning – The authors' proposed concept of muscle tuning suggests that there is a neuromuscular response at or prior to foot contact in running that alters the damping properties of the soft tissue compartments. This limits both the magnitude and number of cycles of soft tissue compartment vibration. The proposed concept of muscle tuning hinges on the idea that im-

part forces must be important in large part because people can perceive differences in them but not for the initially proposed reasons of impact force magnitude related injuries. Prior to the concept of muscle tuning, wobbling mass models (e.g. Cole et al., 1995) of the impact phase in running have been used to understand the determinants of impact force characteristics. These types of models have also shown that soft tissue compartment motion plays an important role in the dissipation of energy upon landing (Pain & Challis, 2002). However, what is not yet known, but critical for understanding the potential importance of designing footwear or apparel for the muscle tuning concept, is the consequences of failing to tune the soft tissue compartments appropriately for landing.

A conceptual framework of the biological relevance for minimizing the soft tissue compartment vibration in running, particularly in the proposed cases where resonance is possible (fast running and low muscle tonus), is needed. As demonstrated by the study using a vibration platform (Wakeling et al., 2002), the body can and does respond to a continuous vibration stimulus. The relevance of this response and negative effects of continuous vibration to the human body is well established from studies of workplace performance and injury. In response to repetitive impacts, anecdotal evidence of injuries in circus athletes due to a non-uniform surface suggests that it is the unexpected landing situation that matters most. Thus, it may follow that the muscle tuning that occurs during running is likely small and may not be relevant for recreational runners. However, in high performance runners, where the risk of resonance may be higher due to faster stride rates and small improvements in efficiency are valuable, the additional muscle activity needed to properly tune the soft tissue compartment may be detrimental to performance. As suggested by the authors, quantifying the muscle tuning response is extremely challenging due to the close coupling of a muscle response to damping vibrations with a muscle response to alter the limb position for landing. While the authors imply that these may be two separate things, the possibility that both: 1) changes in damping; and 2) controlling the impact phase by altering limb geometry, are motivated by a need to minimize soft tissue compartment vibrations should be considered together.

The Preferred Movement Path – In several previous studies (e.g. Nigg, 2001), Nigg suggested that there is a subject and task specific locomotion pattern that is determined by multiple factors (i.e. muscles, tendon, ligaments, bone structure, etc.). He further suggested that this particular motion path may explain why shoes have little or only a moderate effect on lower extremity kinematics (Stacoff et al., 2000). The authors of the current paper suggest that footwear should be designed to facilitate the individual's preferred movement path and that such footwear designs could be energetically advantageous. This is an intriguing hypothesis and, for all practical purposes, makes a great deal of sense. The observed inter-runner variability that results in a mean possibly not resembling any individual in the group may be a result of the individual preferred paths of each of the runners. The major challenge may be determining the in-

dividual's preferred locomotor pattern. One problem concerns the possibility that an individual's movement path can change from one day to another or possibly as a function of fatigue. Thus, we have to ask what is the runner's preferred movement path, does an individual have multiple preferred motion paths (i.e. dependent upon fatigue), and how can we determine that/those path/s?

Functional Groups – Certainly, there may be a group of individuals who respond to a specific shoe intervention in a similar way. The authors have suggested that these individuals form a 'functional group'. This concept is not new; footwear manufacturers have already determined functional groups for those who need cushioning, stability or motion control footwear. However, this grouping is based on old paradigms (i.e. impact loading and pronation). The development of new functional groups requires sound, well-researched paradigms as the authors point out. However, taken to the extreme, a functional group could be a single individual and ultimately we could customize footwear for a single individual.

Conclusion

Many of the implications of previous studies relating footwear and injury risk were derived from extremely small samples thus lacking sufficient statistical power to detect true differences. In addition, many of these studies were retrospective in nature. It is clear that prospective and/or epidemiological studies with large sample sizes are a necessity to discern the link between footwear and injury risk. Large-scale studies (e.g. Nielsen et al, 2014) indicate that the basis for the design of running footwear may have been misguided. It is clear that new paradigms for relating biomechanically informed footwear design and injury risk are necessary.

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Reconciling new with old injury paradigms and the need to dig deeper – comment on Nigg et al.

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ABSTRACT

In response to the target article by Nigg et al (2017) suggesting the need to shift towards new running injury paradigms, we comment on the need to continue investigating a variety of paradigms, new and old, and on poorly studied factors that necessitate the need to continue digging deeper in the pursuit of better prediction of injury development. Lastly, we argue that new and old paradigms can be reconciled under the more general paradigm that running injuries are most directly an issue of tissue adaptation.

Keywords:

Running – injury – movement – loading – adaptation

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Too early to abandon old paradigms

A. Conceptual framework

An established injury paradigm should meet at least two sequential criteria: first, that the effect is real, and second, that the effect can be manipulated in a meaningful way. For example, to establish the impact forces paradigm, it should be shown that (i) impact forces are greater in injury-prone runners than in healthy runners, and (ii) reducing impact forces in injury-prone runners reduces their risk for injury.

B. Usefulness of Incorrect Paradigms

Under the criteria above, we agree that the evidence for the older running injury paradigms of impact forces and ankle pro-

nation broadly explaining the mechanisms of running injury is unconvincing at this time. However, there seems to be little convincing evidence on any particular mechanism of injury in runners to date, so we suggest it is too early to discard any paradigms entirely. Much can be learned from pursuing paradigms that end up being wrong or only situationally correct. For example, the impact forces paradigm was supported in two recent prospective studies on recreational runners (Bredeweg, Kluitenberg, Bessem, & Buist, 2013; Davis, Bowser, & Mullineaux, 2016) but not in two others on competitive collegiate runners (Dudley, Pamukoff, Lynn, Kersey, & Noffal, 2017; Kuhnman, Paquette, Peel, & Melcher, 2016). Rather than discarding this paradigm because all four studies did not support it, we stand to learn more by asking why the studies produced different levels of support:

- (i) Are there sources of false-positives in the former two studies?
- (ii) Are there sources of false-negatives in the latter two studies?
- (iii) Are there plausible mechanisms by which high loading rates would cause injury in recreational runners but not in competitive runners?

Answering these questions could lead to a revised impact forces paradigm, or conception of a new paradigm, even if the original paradigm is not strictly correct.

C. Internal Loading and Tissue Adaptation

Most running injury studies to date have used a “black box” framework where external loading is equated directly with injury risk (Figure 1a). Injuries in theory result more directly from internal loading above the thresholds of frequency and/or intensity for a tissue to experience positive remodeling (Hreljac, 2004). This paradigm is attractive conceptually because it provides a basis for explaining how more specific paradigms predict injuries mechanistically. To better understand the mechanisms of injury under any paradigm, the “black box” should be opened to more directly consider the influence of external loading on internal loading and resulting tissue injury (Figure 1b). The box could be opened conceptually by considering the mechanisms by which an external load may cause injury, by using animal/tissue-level models (e.g. (Loundagin, Schmidt, & Edwards, 2017)), or by using computer models (e.g. (Wright, Neptune, van den Bogert, & Nigg, 1998)). The proposed new paradigms would benefit from including explanations of how

injuries occur mechanistically, how these explanations differ from the mechanisms suggested by older paradigms, and any testable predictions these explanations suggest.

Why We Should Dig Deeper

A. Individual Training Backgrounds or “Functional Groups”

Once we have a better understanding of internal loads associated with running, we can then consider poorly studied factors that can influence the relationship between external and internal loads which may explain curious phenomena in runners. For example, why can some people run with large external impact forces or loading rates without injury? Why can others accumulate massive internal loads without injury? Or why can some individuals run in any old shoe they want without injury? To date, we have limited answers to these questions as research often focuses on injured runners. However, we recommend that we shift our attention to those runners who can seemingly run as much as they want, sometimes in any shoes that they want, to better understand running injury paradigms.

One generally well accepted answer to the questions above is tissue adaptation as a result of gradual tissue loading and adequate recovery. The concept of safe and gradual increases in training workloads for injury reduction has received a considerable amount of attention in team sports (Gabbett, 2016; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016). It is logical that safe and gradual workloads would be an effective strategy to reduce tissue loading and injury development in runners also. Such evidence in runners is still lacking or only anecdotal, but there is some evidence that runners of different training backgrounds and experience run with different movement patterns (Boyer, Freedman Silvernail, & Hamill, 2014; Clermont, Osis, Phinyomark, & Ferber, 2017; Maas, De Bie, Vanfleteren, Hoogkamer, & Vanwanseele, 2017; Verheul, Clansey, & Lake, 2017) that might subsequently alter internal loading of musculoskeletal tissue.

Boyer et al (2014) observed differences in transverse pelvic, hip internal, hip and knee abduction and adduction, and frontal foot rotations between higher (>20 miles/week) and lower (<15 miles/week) mileage runners. These transverse and frontal plane kinematic differences between training groups are suggested to potentially lower risks of knee injury development and may be the result of training-related neuromuscular adaptations as previously observed (Verheul, Clansey, & Lake, 2017). Running ability/performance based on age-graded race times may also influence running kinematics. In general, greater magnitudes of three-dimensional pelvis, hip, knee and ankle angular positions during both swing and stances phases of recreational runners are observed compared to competitive runners (Clermont, Osis, Phinyomark, & Ferber, 2017). Further, less and more experienced runners also appear to adjust their movement patterns differently in response to exhaustive running. Less experienced, or novice, runners run with larger kinematic adjustments in forward trunk lean and swing phase hip

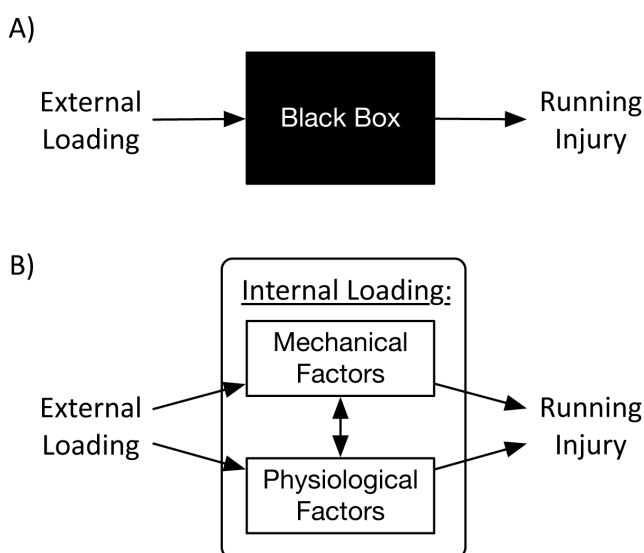


Figure 1: A) The “black box” framework between external loading and injury development, B) The necessary framework to understand the influence of external loading on internal loading, both mechanical and physiological, and resulting tissue injury.

abduction compared to competitive runners during exhaustive running (Maas et al., 2017).

It therefore seems that the concepts of “functional groups”, preferred movement paths and muscle tuning could be explained by the non-linear relationship between internal and external load, different physiological and biomechanical responses to chronic training workloads or exposures, and therefore, reconciling new and old paradigms.

B. Factors That Need More Attention

Defining injuries

Firstly, to have a fruitful conversation on the merits of different running injury paradigms, it is necessary to clearly define what we mean by “injury”. A sensible definition for “overuse running injury” is:

A chronic imbalance in running-induced damage and recovery rates of the affected tissue, resulting in a deleterious change in tissue structure and/or function that limits training ability and/or performance.

This definition seems fairly uncontroversial and appears to have been used at least implicitly in most prior studies. However, large disparities exist in the literature on the criteria used to categorically define a runner as “injured”, e.g. the duration of injury, the means of diagnosis, the severity of symptoms, etc. This lack of uniformity makes it difficult to compare results between studies. There is an evident need for a uniform definition of “injury” to ensure consistent diagnoses in research before we can discard injury paradigms or debate their merits.

Baseline biomechanical and clinical screenings

As recommended by Nigg et al (2017), more prospective studies are necessary to truly identify risk factors, biomechanical or otherwise, responsible for the development of running injuries. Current approaches for such prospective studies on running injuries consist of single-session baseline screenings including gait analyses, and clinical tests followed by survey periods in an attempt to identify predictive factors for the development of injuries. However, a critical flaw to this approach may be that these baseline screens are generally performed when runners are, acutely or chronically, non-fatigued. There is strong evidence for the fatigue- or exhaustion-related changes in running biomechanics especially in novice or recreational runners (Christina, White, & Gilchrist, 2001; Maas et al., 2017; Mizrahi, Verbitsky, & Isakov, 2000; Van Gheluwe & Madsen, 1997). Different approaches for baseline screening procedures including biomechanical or clinical tests performed under acutely (i.e., after single bouts of exhaustive running) or chronically (i.e., after periods of heavy training) fatigued states could provide more sensitive baseline data to identify prospective injury development. Further, multiple testing sessions over a baseline period instead of a single testing session may be more sensitive for prediction of injury development. We acknowledge that such

testing conditions or periods may not be practical for coaches and clinicians but may be necessary in the scientific pursuit of identifying risk factors for running-related injuries.

Summary

In summary, varying magnitudes of internal tissue loading and its resulting tissue adaptation, or lack thereof, to any given novel stimulus (e.g., footwear transitions, gait modifications, higher training intensities and/or volumes) is likely responsible for running injuries. We should consider poorly understood factors including baseline testing conditions in prospective injury studies before discarding old paradigms. Therefore, we must continue to explore both old (i.e., external loads, internal loads, tissue adaptation, non-linear relationship between external and internal loads) and new (i.e., preferred movement path, muscle tuning) running injury paradigms.

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Muscle tuning and preferred movement path: do we need a paradigm shift or should we redefine the old? – comment on Nigg et al.

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COMMENTARY

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ABSTRACT

In the feature paper “Muscle tuning and preferred movement path – a paradigm shift”, Benno Nigg and colleagues discuss that the impact and pronation paradigm should be abandoned as there is not enough biomechanical and epidemiological evidence supporting these paradigms. We agree that the paradigms, as defined in the paper, are currently not supported by strong scientific evidence however we argue that the lack of evidence originates from shortcomings in the methodological approach to these paradigms. In our commentary, we argue for a redefinition of the paradigms rather than defining two ‘new’ paradigms. A better methodological approach and definitions of the paradigms based on the current evidence are needed rather than to abandon them.

Keywords:

Impact – pronation – muscle activation – running – injury – performance

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Introduction

Over the last 40 years, Nigg and his colleagues have made tremendous contributions to the field of footwear biomechanics. They have invested a lot of research and energy in trying to confirm the two “old” paradigms. However, research, novel measurement and analysis techniques have led to new insights and the authors are to be recognized for their courage to step away from the traditional paradigm. We agree with Nigg that good biomechanical and epidemiological evidence behind the pronation and impact paradigm, as defined in the paper, is still scarce. It is however, our opinion that the current lack of evidence is partially due to methodological problems related to the definition and measurement of impact and pronation. We believe that we don’t need to abandon the

old paradigm but need to redefine them using the current scientific knowledge and new methodological approaches.

Impact Forces

Although large prospective studies investigating the link between vertical loading rate and running injuries are lacking, there is some evidence supporting this paradigm. For example, a recent gait retraining intervention study decreasing the vertical loading rates found a decrease in injury risk in novice runners by approximately 22% (Chan et al., 2018). In addition, a recent systematic review (Van Der Worp, Vrieling, & Bredeweg, 2016) supports the association between loading rate and bone related injuries but not with all injuries together.

Therefore, we believe that methodological problems hamper evidence for the impact paradigm especially the *quantification of the loading* and the *definition of injuries*. Using external loading as an estimate of internal tissue loading is limited and more objective ways to estimate internal loading are available. Musculoskeletal modelling and finite element modelling can provide data on internal loading of the musculoskeletal tissue. We acknowledge that these methods require specific expertise, are time consuming, making them less feasible for large cohort studies. However, research combining these models with easier to measure parameters should give further insight in quantifying internal loading. In addition, different tissue are also sensitive to different type of loading. Impact load and rate of loading might be relevant for bone tissue (Edwards, Ward, Meardon, & Derrick, 2009), while muscle activation or moments are more relevant for muscle, ligament and tendinous tissues (Giddings, Beaupre, Whalen, & Carter, 2000).

Muscle Tuning paradigm

In the new muscle tuning paradigm, it is suggested that if the frequency of the external loading is too close to the natural frequency of the soft tissue, muscle activation could reduce soft tissue vibration. Although this is an innovative and interesting concept, similar to the “old” paradigms, it currently lacks scientific evidence especially in running. Furthermore, no experimental or computational studies link tissue vibration with running injuries or performance. The mechanism that muscle activity might change the resonance of the input signal seems to be logical and theoretically sound, however how does vibration of the tissue lead to injury? In this paradigm, more muscle activity will reduce the vibration. Nevertheless, is this increased muscle activation protective against injuries? This somehow seems to be in contrast to the other new “Preferred Movement Path” paradigm, later discussed in this article.

Pronation paradigm

Similar to the loading paradigm, the pronation paradigm is hampered by methodological issues especially in the definition of foot pronation. Foot pronation is a multi-segment triplanar motion, consisting of: subtalar eversion, ankle dorsiflexion and forefoot abduction. However, the majority of early kinematic studies modelled the foot as one rigid segment, and therefore, primarily used rearfoot eversion as a measure of foot pronation (Hintermann & Nigg, 1998). As a consequence, controlling excessive rearfoot eversion has become the focus of many interventions in people with pronated feet (Bishop, Arnold, & May, 2016). We agree with Nigg that the scientific evidence for the relationship between rearfoot eversion and injury risk is weak. We, for instance, found that recreational runners with pronated feet remained asymptomatic despite a larger rearfoot eversion during gait compared to their counterparts with neutral feet

(Zhang, Aeles, & Vanwanseele, 2017). This raises doubts on rear-foot eversion as indicator for overuse injury risk. However, using a multi-segment foot model, we demonstrated that symptomatic runners have larger transverse plane forefoot motion (unpublished data). As forefoot abduction is a component of foot pronation, it does not seem appropriate to abandon the pronation paradigm but rather to adopt a better definition and use multi-segment foot models to investigate this paradigm further. Moreover, interventions targeted at foot pronation should take into account the complex nature of the foot and not only focus on rearfoot eversion.

Preferred Movement Path

The preferred movement path is defined as a movement path that an individual chooses due to either minimal resistance, maximal comfort, or least energy demand (Nigg et al., 2017; Nigg, Baltich, Hoerzer, & Enders, 2015). We believe that this paradigm is conceptually innovative in its break away from the traditional paradigms and its novel outlook on movement control. However, as it currently stands, we feel that this paradigm is still very much in its research infancy and requires more clarity. We would also argue that the word ‘preferred’ 1) qualitatively needs a better description and 2) quantitatively needs better criteria to set critical thresholds. As such, we analyze the preferred movement path by posing a few questions, and where possible, suggest clarification of the paradigm to direct future research.

Qualitatively, what is “preferred?”

On the one hand, preferred could refer to ‘natural’, that is, the unshod barefoot condition. On the other hand, ‘preferred’ could also refer to ‘habitual’, that is, the particular footwear or running surface condition that the individual has experience with and thus has become trained to or adapted to. Adoption of one of these opposing terms may improve the interpretation as to what constitutes the baseline of the ‘preferred’ condition. As a thought experiment, consider a runner who trains in multiple types of footwear and on multiple terrains. How would one define this particular runner’s ‘preferred’ movement path? A ‘habitually-preferred’ movement path would essentially be one that is highly dynamic with an ever-changing baseline, a challenging feat to quantify and thus one that we would not advocate. Hence, to avoid ambiguity, we would avoid using ‘habitually-preferred’ and rather suggest a ‘naturally-preferred’ movement path.

Conceptually, the barefoot condition is innate to every individual. Methodologically, barefoot is unconstrained to any footwear characteristics, and therefore easy to standardize or generalize across individuals and laboratories. This ‘naturally-preferred’ condition could provide a good baseline to classify individual’s into what Nigg coined as ‘functional groups’. For instance, grouping individuals by evaluating their kinematic

response to particular footwear types versus barefoot as the baseline. Therefore, the optimal footwear condition would be the one where the kinematic response deviates the least from natural condition.

Quantitatively, what is "preferred?"

Firstly, how much deviation from 'preferred' is too much? In a recent paper, Nigg (Nigg et al., 2017) arbitrarily set 2, 3, and 5 degrees as thresholds for staying within the preferred movement path between running footwear conditions. However, it is not clear whether the magnitudes of these thresholds in absolute terms are generalizable between joints and planes of motion. For example, one could argue that 3.7 degrees change in ankle adduction is quite large compared to the same change in knee flexion. Interestingly, one study (Schrödter, Brüggemann, Hamill, & Rohr, 2016) has provided a first step towards functional meaning of the paradigm by demonstrating that knee extensor strength was associated with the footwear-related variability (as a measure of deviations from the preferred movement path) of the hip and knee while running in six different types of footwear. However, what appears to be lacking are studies that can identify a 'critical' threshold in relation to injury risk, both retrospectively and prospectively.

Secondly, what specifically is the most appropriate measure to quantify 'deviation' from one's preferred movement path? Nigg (Nigg et al., 2017) used the mean absolute difference while other researchers have used the magnitude of "footwear-related variability" for a given joint angle or moment during stance phase (Schrödter, Brüggemann, Hamill, & Rohr, 2016). Recently, our research group has shown that other measures (e.g., acceleration waveform complexity, variability, stability) could alternatively be used to quantify deviations in a runner's movement path in relation to outdoor running fatigue and injury history (Schütte, Seerden, Venter, & Vanwanseele, 2017). Future research is therefore encouraged to explore other measures that could shed additional light into determining a runner's movement 'path' in the real world.

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All relevant data are within the paper.

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Response to select comments on the proposed paradigm shifts in running

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Introduction

This publication is a reply to comments made by six experts in the field of running and running shoe construction (Becker, 2018; Clark, Udofa, Ryan, & Weyand, 2018; Federolf, Doix, & Jochum, 2018; Hamill, Boyer, & Weir, 2018; Paquette & Miller, 2018; Vanwanseele, Zhang, & Schütte, 2018) regarding the proposal of replacing the paradigms of impact force and pronation control with some new paradigms (B.M. Nigg, Mohr, & S.R. Nigg, 2017). The comments of the experts can be summarized as follows:

(1) External impact force variables have not been correctly assessed and/or their relationship with internal loading has

ABSTRACT

Background: Six experts in the field of running-related research have critically addressed a proposal to abandon the paradigms of 'impact force' and 'pronation control' when investigating running shoes, running injury, and running performance. Further, these experts have commented on the suggestion of the new paradigms of 'muscle tuning' and the 'preferred movement path' that can be used to investigate questions related to running injuries and performance as well running shoe design and comfort. This publication synthesizes and addresses the main criticisms of the experts and describes future directions to further develop the 'muscle tuning and 'preferred movement' paradigms.

Keywords:

Impact forces – pronation – running biomechanics – running injuries – running performance – running shoes

not been considered. This has hampered the analysis of the association between impact forces and running injuries and thus, the 'impact force' paradigm should not be abandoned (Becker, 2018; Clark et al., 2018; Paquette & Miller, 2018; Vanwanseele et al., 2018).

- (2) The methods to quantify muscle tuning and the preferred movement path (PMP) along with the predictions that can be made from this paradigm need to be improved/developed (Federolf et al., 2018; Hamill et al., 2018; Vanwanseele et al., 2018).
- (3) The traditional variables to quantify pronation are not valid and do not adequately describe foot movement or the relative movement of foot and shank segments. Therefore,

the topic of foot movement and injuries should be re-evaluated (Becker, 2018; Vanwanseele et al., 2018).

(4) The association of the proposed new paradigms with running injuries was a main topic of all comments. In principal, we agree with comments 1-3 above. With respect to comment 4, we agree that the proposed paradigms can be used to formulate hypotheses related to running injury mechanisms, but also want the readers to consider other potential outcomes like the effect on performance or comfort. We hope that the result of this process and these papers will lead to a better understanding of running related questions. Detailed replies to each of the four generalized comments follow.

1.1 *The difference between external and internal impact forces*

Running paradigms can be used to formulate hypotheses about mechanisms related to running injuries. Locomotion related injuries should always be discussed from the perspective of tissue loading and tissue adaptation (Hreljac, 2004; Paquette & Miller, 2018). If the tissue is loaded in a way that results in a more rapid tissue breakdown compared to the rate of tissue regeneration, an injury of that tissue will follow eventually. If a runner increases his/her exercise volume and frequency too fast so that tissue adaptation and regeneration cannot occur, the runner will get injured. From this perspective, different mechanisms have been suggested for loading scenarios that will make an injury more likely to occur, e.g. high magnitude and rate of impact loading, the failure to adequately tune muscles, excessive foot movement, deviation from the preferred movement path and others. All these mechanisms are lacking experimental evidence regarding how they affect tissue-level strains. Therefore, we should acknowledge that efforts must be made to investigate the relationship between external variables (e.g. ground reaction forces, joint angles, segmental / soft-tissue accelerations) and tissue-level strains. This knowledge can be gathered by using 1) model calculations to determine internal forces and stresses *in vivo* (e.g. Wright, Neptune, van den Bogert, & Nigg, 1998) and 2) mechanical tests to study the relationship between tissue loading profiles (i.e. magnitude, rate, frequency, duration) and tissue failure *ex vivo* (e.g. Edwards, 2018). One key result from the second approach illustrated that the influence of the ground reaction force loading rate on the fatigue behavior of bone may be negligible compared to the influence of the loading magnitude (Loundagin, Schmidt, & Edwards, 2018). In other words, we now have evidence that increased loading rate may not correlate well to damage at the bone tissue level. By conducting similar investigations, we have the ability to systematically investigate hypotheses regarding the relationship between external loading rate signals and the risk for specific injuries.

Since the relationship between external ground reaction forces (which are integral variables) and internal forces (which are local variables) is typically not very strong, it seems inappropriate to use external force variables to predict the development

of internal injuries. Most reviewers agreed on this, and thus statements like “excessive impact loading causes running injuries” should be avoided.

The original impact force paradigm has been formulated using the externally measured ground reaction forces and their maximum peak, the impact force peak, and/or their maximal or average first derivative, the (external) loading rate. It is well understood that the ground reaction force during landing in running is the sum of many different components, the two most important components being the acceleration of part of the lower leg and the accelerations of the rest of the human body. The contribution of the foot and leg has originally been described using the effective mass model (Denoth, 1986). The combination of these two major force components has been illustrated and explained and is well understood (Shorten & Mientjes, 2011). There is no disagreement about the combination of these forces into a resultant ground reaction force. The possible disagreement is the interpretation of the initial peak. Some researchers suggest that the impact force component and the force component due to the rest of the body should be considered separately (Shorten & Mientjes, 2011; Clark et al., 2018). Two comments seem to be appropriate: (a) To determine the loading on an internal structure of the athlete's body, one needs a model that calculates/estimates these internal loadings and this model would, most likely, use the resultant ground reaction force as an input. (b) Experimenting with the effective mass model or with the actual lower leg initiated force component may be helpful in understanding how the impact force can be influenced and/or in understanding how certain shoe construction elements influence the external loading. However, to assess the actual loading of biological structures one needs a biomechanical model using the actual ground reaction forces as indicated above.

1.2 *The impact force paradigm should not be abandoned*

The impact force paradigm as currently formulated states that high external impact force peaks and high external loading rates are the reason for running injuries. We have shown that functional and statistical evidence for such a statement is missing. Consequently, we have argued that the impact paradigm in its current form, i.e. that the early peak in the external ground reaction force causes injuries *per se* should be abandoned.

We do not generally reject the idea that impact loading could be important for running mechanics and running injuries. Instead, we argue that the traditional measures of external impact loading are not useful in describing underlying biomechanical phenomena and thus should not be used as a starting point to investigate running mechanics and/or running injuries. The ground reaction force is a variable that has magnitude, frequency and variability. These aspects may and most likely will help us to understand the neuro-motor and loading aspects during running. Further, these aspects are not solely associated with running injuries, but rather relate in a much

broader sense to the understanding of the biomechanical and neuro-motor aspects of running (Federolf et al., 2018). To understand the risk factors for running injuries, however, we should concentrate on variables that quantify internal loading.

2.1 Muscle tuning and predictions

The fact that we adapt our muscles for any activity has not been challenged. However, the practical implication of the proposed muscle tuning paradigm remains unclear (Hamill et al., 2018; Vanwanseele et al., 2018). We are used to accept changes in muscle activity due to a specific change in movement (e.g. walking versus hopping). However, we are not used to think of such changes due to other reasons within the same movement task. Furthermore, the concept that vibrations of soft tissue compartments may affect our muscle activities is novel to many.

The authors agree that working on this topic exceeds the typical comfort zone of biomechanical studies. However, we think that this topic is important, especially from an energy and fatigue point of view. The athletes know what to expect when running and they adapt quickly to changing situations. We suggest that there are two reasons for changes in muscle activity; a) to satisfy the mechanical requirements when movement changes, and b) to minimize large soft tissue compartment vibrations. Our proposed “muscle tuning paradigm” suggests that runners activate specific muscles if the frequency of the input force (impact) is close to the natural frequency of these soft tissue compartments and the vibrations of these compartments could become excessive. “Reacting” corresponds to increasing the damping of these muscles or changing the natural frequency of the soft tissue compartment. Both situations correspond to a change in muscle activity and both situations correspond to a change of the muscle-tendon unit characteristics (Federolf et al., 2018). One major problem when working on the concept of muscle tuning is that these muscle activity changes cannot easily be differentiated. However, for running shoe construction one has theoretically two possibilities: (a) One can change the natural frequency of the soft tissue compartment by increasing/decreasing muscle activity and/or (b) one can shift the frequency of the input signal so that it is far away from the natural frequency by changing the running mechanics (e.g. the running kinematics or the running shoes). Based on results of initial experimental results, the first strategy of changing the natural frequency of the soft tissue compartments is rarely used by athletes. This leaves the second possibility, i.e. changing the input frequency. Preliminary experiments where shoe properties were altered with the objective of reducing soft-tissue vibrations, showed a decrease in vibration energy of 5dB, a substantial reduction when compared to normal running shoes. Two important additional comments in this context are 1) that the individually correct changes in input frequency can be an increase or a decrease in the input frequency depending on the runner’s anthropometric characteristics, and 2) the strategies to move away from the resonance phenomena are

individual by nature, meaning there is not one solution for all runners.

2.2 Muscle tuning and running injuries

It should be emphasized that the proposed muscle tuning paradigm is not equivalent to a possible explanation for an injury mechanism. Instead, the muscle tuning paradigm aims to describe basic neuromuscular strategies of the motor control system during movement. However, the paradigm can be used as a framework to formulate hypotheses about how the risk of injury can be reduced or how comfort or performance during running can be improved – particularly with a focus on how footwear can be used to achieve this. This means that questions in running biomechanics / motor control can be structured into one of two categories: (1) Questions that further advance our understanding of basic neuromuscular strategies during running or (2) questions about how certain biomechanical variables affect injury risk, performance and/or comfort. Based on our current knowledge and based on theoretical considerations we tend to see the application more in the energy/performance and comfort field than in the injury field.

2.3 Preferred movement path and predictions

The proposed paradigm of the “preferred movement path” was generally well accepted by the expert panel. The major concern was how to determine the preferred movement path (e.g. Hamill et al., 2018). Furthermore, it was suggested that the variability of the actual movement path should be included in further studies (Federolf et al., 2018; Vanwanseele et al., 2018). We agree that the concept of the preferred movement path is currently not easily quantified. At this point in time there is (in the view of the authors) no valid method available to determine and/or predict the preferred movement path. We suggest that the concept of the preferred movement should be investigated by analyzing not only the movement but include muscle activity in the experimental set-up. We recently showed that the muscle activation patterns of the vasti muscles during running may be highly variable but non-random between steps (von Tscharner, Ullrich, Mohr, Marquez, & Nigg, 2018). This may reflect the strategy of the motor control system to maintain the preferred movement path by continuously adjusting the activity of leg muscles in response to slightly different external forces at each heel strike. The goal of further studies should be to investigate the link between variability in muscle activation patterns and variability in segment kinematics. According to the PMP, there should be a relationship between the two variables.

If the influence of external conditions on the runner is small, substantial neuromuscular adjustments to maintain the PMP are not required. In this case, the integrated muscle activity should be minimal. We suggest, that the measurement of running kinematics and muscle activation patterns in conjunction with global oxygen consumption could provide further insight

into this prediction of the PMP and its relationship to energy expenditure.

Furthermore, it has been proposed (Federolf et al., 2018) that joint angles should not be viewed in isolation. Instead, the simultaneous coordination of multiple joints and segments should be of interest. Finally, it should be studied whether the preferred movement path changes or remains with increasing fatigue.

2.4 Preferred movement path and running injuries

The preferred movement path paradigm has been proposed to improve the understanding of the biomechanical and neurophysiological aspects of running (similar to the muscle tuning paradigm). Whether or not it is associated with the development of running injuries is not clear to the authors at this point in time. Theoretically, one should expect that running outside of one's preferred movement path would increase the muscular demand and, therefore, increase fatigue (Paquette & Miller, 2018). Further research is needed to clarify this aspect.

3.1 The traditional pronation variables do not adequately describe the foot movement

There seems to be general agreement that the variables currently used to assess pronation are questionable. Further support for this general "feeling" has been provided through the results of a recent study analyzing 62 currently used "pronation variables" (Behling, von Tscherner, Manz, & Nigg, 2018). The results of this study showed no strong or moderate correlation between different variables. This means that the commonly used variables used to describe the term pronation, are actually describing different aspects of foot movement and may even not be associated with foot pronation. There seems to be agreement in the responses of the experts that this aspect requires further analysis and that the current approaches are not helpful in understanding "pronation" and its relationship (if any) with running injuries. We suggest that further studies should concentrate on "foot movement" and not on "pronation", and that the foot movement should be segmented into different aspects (forefoot, midfoot, and calcaneal), in order to better understand each segment of the foot, and the relationship between those segments.

3.2 Pronation and running injuries

The epidemiological studies assessing "pronation" as a risk for running injuries show the same problems as the epidemiological studies for impact loading. The studies use typically small subject samples and consequently, the results are random and can not be used for strong predictions. There is, however, one study that has a large sample (927 participants and 1854 feet) that provides enough statistical power to answer the injury risk question (Nielsen et al., 2014). They showed that

people that "pronate" have the lowest injury risk. Furthermore, they showed that people that have excessive pronation only represent about 1 % of the population, and these individuals did trend to being susceptible to injury. The results of this study seem to answer the question whether "pronation" is an injury risk – yes if extreme, no for the average runner. However, the study has some shortcomings. The "pronation" was quantified using the FPI (foot posture index). The FPI is a static variable and is one of the variables that does not have any correlation with the other commonly used "pronation" variables. Thus, we don't know, whether or not the FPI actually quantifies "pronation". Consequently, it is fair to state that any proposed injury risk factors related to "pronation" should be treated with caution, unless we are dealing with a small sub segment of the population.

We suggest that a good understanding of the **detailed foot movement** (forefoot, midfoot and rearfoot) and its relationship to internal tissue loading (Becker, 2018) may help to improve the understanding of possible injury mechanisms.

4 The proposed paradigms and running injuries

In our opinion (and in agreement with Becker, 2018 and Paquette & Miller, 2018) injuries should always be discussed from the perspective of tissue loading and tissue adaptation. Efforts must be made to investigate tissue-level strains or local loading.

It is important, however, to avoid generalizing statements about running injuries such as 'excessive foot movement causes injuries' or 'gait training reduces injuries in novice runners' (Chan et al., 2018). Hypotheses must be specific for individual running-related injuries. For example: 'Tibialis posterior muscle weakness may result in lower longitudinal arch stiffness and therefore higher plantar fascia strain during running and thus plantar fasciitis'. Or: 'The necessity to tune the calf muscles, e.g. when the input force signal during running would otherwise cause resonance effects, increases calf muscle strain and subsequently causes calf strain injuries'. Such hypotheses would be helpful to advance our understanding, the prevention and treatment of running injuries.

In summary, more studies for improving the understanding of running injuries are needed. Large prospective epidemiological studies using model calculations to determine internal loading may not be feasible. Therefore, one may want to structure future running injury research in two steps: (a) Studies with relatively small sample sizes under controlled conditions to identify external biomechanical variables that are highly correlated with internal loading and (b) Large epidemiological studies that use these external variables, restricted to one injury based on a functional understanding of the possible injury mechanism.

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Competing Interests

The authors have worked over about 40 years with more than 40 industry partners. Many of these contacts were paid for by these partners. Results and understanding from projects with these partners have influenced the development of the paradigms, presented in this paper. However, the authors declare that no competing interests exist.

Data Availability Statement

All relevant data are within the paper.

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