IMPACT FORCES AND MOVEMENT CONTROL - TWO NEW PARADIGMS

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INTRODUCTION: In the last century, participation in physical activities has developed dramatically. The best documented development was in running with millions of participants (6, 24). Between 1978 and 1983, the number of runners in Canada has more than doubled from 15 % to 31 %, but has decreased in 1988 to about 18 % of the total population (50, 56). The high incidence of injuries in runners has been proposed as one possible reason for this decrease. Between 37 to 56 % of all runners are injured during a year of running (31) and running injuries make up the majority of sport related injuries in the young (31.5 %) and the old (40.5 %) physically active population (29).
Major reasons for the development of exercise related injuries proposed in the literature include previous injuries, training errors, excessive impact forces and excessive foot movement or movement control (8, 9, 21, 31). From a biomechanical point of view impact forces and movement control are of interest since they can be influenced with the sport shoe. This paper will concentrate on these two aspects and propose two new paradigms for the functional understanding of impact forces and movement control.

IMPACT FORCES, SOFT TISSUE VIBRATIONS AND MUSCLE TUNING: Based on the idea that impact forces are associated with the development of running injuries, the concept of "impact cushioning" was developed and strategies were proposed to reduce potentially excessive impact forces through appropriate running shoe and sport surface designs.
However, a wealth of experimental and epidemiological results, even considered in their limitation (limited sample size, type of injuries, uncontrolled boundary conditions) could not establish a correlation between impact loading and specific exercise related injuries, indicating that the concept of "impact forces" may not be well understood. The experimental and epidemiological results indicated that the paradigm of "cushioning" (the reduction of the impact force amplitude) to reduce the frequency or type of running injuries should be reconsidered (39).
Impact forces - surprising results: Initial research on impact forces during athletic activities (mostly for heel-toe running) provided often rather surprising findings.
External impact forces: About 81 % of all runners/joggers impact the ground initially with the heel (22). The foot and the leg are typically decelerated in less than 50 milliseconds producing an impact peak (3). Running velocity affected the vertical impact force peaks and loading rates substantially (15, 19, 36). External impact force peaks, F_{zi}, were relatively insensitive to changes in the hardness of shoe midsoles (7, 35). Changes in midsole hardness affected in some cases the external loading rate, $(dF_z/dt)_{max}$ (11, 14, 25, 27, 29).
Internal impact forces: Internal impact force peaks in the ankle and subtalar joints were relatively insensitive to changes in hardness of running shoe midsoles (5, 20, 32, 47). The magnitude of joint contact forces in the ankle and subtalar joints was substantially (2 to 5 times) smaller during the impact than during the active phase of running (32). Thus, normal impact forces might not be related to the development of movement related injuries of structures of the lower extremities (47).
Epidemiology: The frequency of osteoarthritis was about equal in runners and non-runners (12, 23, 26, 43). Running on hard surfaces did not result in an increase of running injuries if compared to running on softer surfaces (31). Shock absorbing insoles were not effective in reducing the incidence of stress fractures in military recruits for which they were originally designed (16, 46). Results of a prospective study showed no significant difference in short termrunning injuries between subjects with high, medium and low impact force peaks (1, 39). The same prospective study showed that subjects with a high vertical loading rate, $(dF_z/dt)_{max}$, had significantly fewer (only about 50%) running related injuries than subjects with a low loading rate.

Energy and Muscles: Model calculations for systematic variations of the mechanical properties of the shoe-surface interface (38) suggested that the selection of elastic or visco-elastic shoe sole materials influenced the energy and work requirements in running (41). Changes in impact force input into the foot produced substantial and subject specific changes in myoelectric activity before and/or during ground contact (39).
Biological reactions: High impact activities such as forces in running or gymnastics or dancing typically increased skeletal mass while low impact activities such as swimming did not seem to provide the same positive effect (17, 18). Repeated application of a force with a 1 Hz signal frequency was not able to maintain bone mass while the same procedure with a 15 Hz signal frequency stimulated substantial new bone formation (30). Results for biological reactions of impact loading were consistently positive for bone. However, they were inconsistent for cartilage and are still open to discussion (e.g. 44, 45).
Conclusion from the experimental results: Based on the presented results one cannot conclude that repetitive impact forces are a major factor in the development of chronic and/or acute running related injuries. Excessive impact forces may produce damage to the human musculo-skeletal system. However, there is a window of loading in which biological tissues react positively to repetitive impact loading. Based on the current knowledge it is speculated that repetitive impact loading for cartilage and soft tissue structures falls within the acceptable window for moderate and intensive exercise and sport activity and that impact loading for bone may sometimes fall outside the acceptable window for intensive activities with inappropriate recovery periods.
Impact forces, soft tissue vibrations and muscle tuning: Running in soft shoes creates a different comfort feeling than running in hard shoes. There is strong evidence that these "feelings" and the experimental (kinetics and epidemiology) results for impact forces can be explained with the new paradigm of soft tissue vibrations and related muscle tuning (37, 39):

1) Impact forces during heel strike are an input signal with amplitude and a frequency.
2) Impact forces produce vibrations of the soft tissue packages.
3) Muscles attempt to minimize vibrations of the soft tissue packages by changing their natural frequency and/or the damping characteristics (muscle tuning).
4) Changes in muscle activity are large when the frequency of the input signal (impact force) is close to the natural frequency and small when the input frequency is clearly different from the natural frequency of a specific soft tissue package.
5) Changes in input signals may have an effect on fatigue, energy/performance and subjective comfort.
6) Changes in muscle activity are subject-specific and different for different soft tissue packages.

Results from many studies in our Laboratory provide strong evidence for the proposed paradigm. For example:
Direct evidence:
(a) Movement of soft tissue packages can be described using a damped linear oscillation (51, 52, 53). Soft tissue movement immediately after heel-strike is small and short. This is in support of the suggestion that the locomotor system tries to minimize soft tissue vibrations.
(b) Changes in EMG activity have been studied in a quasistatic experiment for systematically varied input frequencies (10 - 65 Hz) into the human foot (54). The test subjects were standing on their toes on a vibration platform exposed to vibrations with different frequencies. The results of this experiment showed clearly (i) a resonance frequency for the tested soft tissue package, (ii) an increased power dissipation around the resonance frequency of the soft tissue package and (iii) an increased EMG activity compared to no vibration input. These results reflect exactly what has been proposed in the new paradigm.
(c) Adaptation of EMG activity (while maintaining a constant vibration amplitude) have been shown for fast heel-toe running with different mid-sole hardness (4) and for walking (55) with two shoes with different heel hardness. In both studies, EMG intensity increased when the frequency of the input signal approached the natural frequency of the soft tissue packages.

Indirect evidence: Changes in oxygen consumption have been measured (41) in two experiments with subjects running on a treadmill with shoes that were identical except in their heel materials (elastic and visco-elastic). The results of these experiments suggest that the tested changes had positive or negative effects on the oxygen consumption depending on the subjects. The different "feeling" while running on soft or hard surfaces or shoes may be associated with changes in muscle activities and related changes in the soft tissue vibrations, both influenced by the impact input.

Final comments for impact forces: Assuming that the new paradigm of impact forces is valid, the following conclusions seem appropriate:

- Impact forces during normal sport activities such as running should not be expected to be a prime reason for the development of exercise/sport related injuries.
- Impact forces in sport activities are important because of (a) stimuli to the bone and (b) soft tissue vibrations and the related muscle tuning.
- Impact conditions may have an effect on work, performance and comfort.

The new paradigm on impact forces and soft tissue vibrations may also explain the (in many circumstances) surprising effects of viscous shoe and surface materials. The viscous material could act like a low pass filter and cut out the high frequencies. Furthermore, the new paradigm stresses the importance of appropriate impact conditions and indicates that there is much potential in using improved materials for sport surfaces and sport shoes.

MOVEMENT CONTROL OR DO SHOES/INSERTS AND ORTHOTICS ALIGN THE SKELETON?: Special shoes, inserts and orthotics have been advocated and successfully used for many years. Their administration or prescription has been and is done for many different reasons, including reducing impact forces (28), reducing muscle activity (34), reducing joint moments (10) and aligning the skeleton "properly". The effects of foot orthoses on the alignment of the skeleton are contradictory (e.g. 13, 49, 33). Thus it seems appropriate to discuss the aspect of skeletal alignment in more detail. The purposes of this chapter are (a) to discuss the influence of shoes, inserts and orthotics on aligning the skeleton and (b) to propose a new paradigm addressing the functional effect of shoes, inserts and orthotics.

Surprising results: Many sports related injuries have been associated with biomechanical deficits such as the static or dynamic mal-alignment of the skeleton and resulting overuse of the skeleton (e.g., 8, 21). Excessive foot eversion and/or tibial rotation movements have been proposed to increase the chance of overuse syndromes such as patello-femoral-pain-syndromes, shin splints, Achilles tendonitis, plantar faciitis and stress fractures. It was in this context that the proper alignment of the skeleton has been proposed as one of the most important functions of shoe, inserts and orthotics. However, some results of previous studies suggest that this concept should be critically revisited since there are several surprising results.

Reduction of foot eversion: Reduction of foot eversion with inserts or orthotics has been assessed in various studies (13, 34, 48, 42, 2, 49). The results of these studies showed that differences in foot or shoe eversion between the orthotic and the non orthotic conditions were sometimes significant and sometimes not. In all studies where the skin or the bone movement was quantified (instead of the shoe movement) only one orthotic condition showed significant differences (33) and the orthotic was a posted condition. However, the differences were always small (less than 2 to 3 degrees).

Injury frequency: Foot and ankle alignment was assessed in a prospective study at the start of a 6 months running activity (40). The results of this study showed that foot and ankle eversion were not a predictor for movement related injuries.

Skeletal movement: Changes in skeletal movement due to shoes or inserts were quantified with the help of bone pins in the calcaneus, tibia and femur (13). The results of this study showed that differences of skeletal movement due to shoe inserts were small and not systematic.

Preferred movement path: Studies using cadaver specimens showed that every joint has a preferred movement path (57), the path of least mechanical resistance. Thus, every deviation from this preferred movement path requires a force. In the in vivo situation, an orthotic may produce force situations that would force the joint movement out of the preferred movement path.
Conclusions from the experimental results: Based on these considerations one may question the idea that a major function of shoes or orthotics would consist in aligning the skeleton.
Proposed Concept for Inserts and Orthotics: The experimental results indicate that the skeleton changes its path of movement for a given task only minimally when exposed to an intervention (shoe, insert or orthotic). Thus, it seems feasible to propose and discuss a new paradigm for sport shoes, inserts and orthotics, the paradigm of ***minimizing muscle work*** when using a specific sport shoe, insert and/or orthotic. It is proposed that the actual function of a sport shoe, insert and/or orthotic is as follows:
(1) Every joint has a preferred skeletal movement path for a given movement task. For a given point the musculo-skeletal system attempts to remain in the preferred movement path.
(2) If an orthotic intervention supports the preferred movement path, muscle activity is not needed to keep the joint movement in the preferred movement path. If an orthotic intervention counteracts the preferred movement path, muscle activity will be increased to avoid a change in the actual movement path in a joint.
(3) Thus, an optimal shoe/insert/orthotic condition reduces muscle activity that is not movement related.
(4) An optimal shoe/insert/orthotic condition feels comfortable because additional (not movement task related) muscle activity and the resulting fatigue are minimized.
5) Since total muscle activity is minimized performance should increase with an optimal shoe/insert/orthotic condition.
Evidence: The proposed concept for the function of sport shoes, inserts and/or orthotics has been supported by some initial evidence. Probably the strongest evidence today is the fact that orthotic interventions change the actual movement only minimally. However, more and stronger evidence must be provided to support or reject the proposed concept.

SUMMARIZING COMMENTS: The two proposed new paradigms have one aspect in common: They concentrate on the reaction of muscles to an input signal. Initial work on impact loading and movement control concentrated on skeletal aspects. This approach concentrates on muscles. For both paradigms the optimal situation corresponds to a not task related muscle activity that is minimal.
The supporting evidence is rather convincing for the paradigm of muscle tuning but rather thin for the paradigm of movement control. Further studies should concentrate on providing more supporting or contradicting evidence.

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