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TISSUE RESPONSE TO IMPACT LOADING IN SPORTS

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The response of biological tissue to impact like mechanical loading in sports is of vital interest in sports biomechanics, athletic training research and especially the development of an injury reduction model. Bone and articular cartilage react differently to mechanical loading in the long term. A strong association to the loading patterns for the response of bone but not for that of cartilage has been be identified. For the short term experimental results provide evidence on two different articular cartilage responses related to loading regimes (high frequent impact vs. low frequent impact). From the reported results the risk of overuse through impact loading was derived as a function of sports related impact loading patterns and subject specific prerequisites.

KEY WORDS: Impact loading, high and low frequency impacts, cartilage, bone

INTRODUCTION: This contribution discusses the association between impact like mechanical loading in sports and the response of biological tissue to single and repetitive impact applications in a short and a long term perspective. The focus will be on variables describing impact loading and on biomarkers indicating the biological reactions. The review of the impact related responses of biological structures will concentrate on bone and articular cartilage, two biological tissues which might be of major interest in relation to overuse and injuries due to sports and exercise. The experimental data presented condense the articular cartilage due to the fact that the literature review identified a wide number of unsolved problems and unanswered questions related to the cartilage tissue response to dynamic mechanical loading in sports and the tissue potential for morphological and functional adaptation.

IMPACT LOADING: Impact loading in sports is obviously related to running or landings and often discussed in relation to the mechanics of athletic shoes or playing surfaces cushioning. The ground reaction forces recorded during heel-toe running have a characteristic pattern that scales with body mass and running speed (e.g. Hamill *et al*, 1983). Nigg (1997) first described the two distinct peaks as “passive” and “active” phases. The “passive” phase reflects the initial impact between the body and the ground. The impact forces’ characteristics (e.g. amplitude, loading rate) are strongly determined by the initial conditions of impact which means by the initial body’s kinetic energy or the velocity of the landing body segment and the system’s stiffness. The stiffness of the landing body (e.g. leg stiffness) is strongly related to muscle activation and co-contraction prior to the foot landing. The impact forces are described as the forces resulting from the collision of the foot (or even the heel) with the ground, reaching their maximum (impact peak) earlier than 50 ms after the first ground contact with the foot (Nigg, 2001). If the ground reaction forces during impact are simplified as sinusoidal waveforms, their frequency content is generally between 10-20 Hz and increasing with running or landing speed. The active phase reflects the propulsive forces applied by the musculo-skeletal system and is strongly related to muscle forces. When considering the ground reaction forces in human locomotion, physical activity and sports many of such activities are related to force time histories which have only few contribution of high frequency components >12 Hz (Shorten, 2002). Such activities with a valuable contribution of high frequency components are related to extreme initial energy from a fast run-up (e.g. long jump or triple jump) or from a landing from a height (e.g. landing from a dismount in gymnastics or landing from a jump in basketball). The majority of dynamic human performances in sports and physical activity compose mainly dominant ground reaction force in a frequency spectrum of 2.5 to 5 Hz. Vertical ground reaction forces in take off in gymnastic tumbling which is used in the literature as a typical impact related sport (e.g. Grimston & Zernicke, 1993) is characterised by a signal frequency of 4 to ≤5 Hz (Brüggemann & Krahl, 2000), and most of the activities in games sports show a signal frequency of the ground reaction forces which contributes mainly frequencies of ≤5 Hz. Therefore the majority of activities which are use in the literature related to tissue response to mechanical stimuli are not impact like loadings related to the definition above. Assuming that biological reaction to mechanical loading is related to the loading amplitude and the signal frequency of the mechanical stimulus and in order to increase the access to biological responses to mechanical loading in general we propose to differentiate between an high frequency impact loading (HFI) behaviour at signal frequency >5 Hz (generally 10-20 Hz (Nigg, 2001)) and a low frequency impact loading (LFI) at signal frequencies at 2.5 to 5 Hz, which can also be named “bounce” type loading. Forefoot running for example is a bounce type mechanical loading whereas heel-toe running contains at least a percentage of impact type loading. Landing from a jump or a height typically is an “impact” type stimulus at ≥10 Hz. Most of the sports have only a little contribution of HFI-loading. Examples for higher percentage of HFI are the jump and/or landing related disciplines in track and field (long jump, high jump, triple jump and pole vault), in gymnastics (floor exercise, vault and the dismounts from the apparatus), and in game sports (basketball, team handball). The majority of game, team sports and running related sports are mainly related to LFI loading, in which the muscle contribution to bone and articular cartilage loading plays the dominant role.

TISSUE RESPONSE TO IMPACT LOADING: Impact loading and response of bone: For repetitive impact force application like in heel-toe-running impact forces have traditionally been proposed as one major reason for the pathological response of biological tissue and the development of running injuries (van Mechelen, 1992; Whittle, 1999). However, a recently performed meta-analysis on the relationship between lower extremity stress fractures and ground reaction forces (Zapoor & Nikooyan, 2010) do not support the hypothesis that there is a significant difference between the ground reaction force of subjects experiencing lower-limb stress fractures and control groups. One can conclude that it is not finally shown that “impact” loading in normal locomotion, physical activity and sports is strongly related to overuse bony structures and to traumatic and especially fatigue injuries. For the bone the results can be summarized as follows: Mechanical stimuli of have been shown to improve bone integrity. Impact activities as gymnastics, basketball, running or dancing typically produce an increase in skeletal mass, while athletes involved in low impact activities such swimming often have low bone density (Grimston & Zernicke, 1993). Intense exercise in young men (army recruits) stimulated increases in bone mineral density (Leichter *et al*, 1989), while moderate and impact free exercise regimens generally results in only modest, if any, increases in bone mass. A positive biological bone response in regard to an increased strength and/or bone mass might be related to exceptionally few high strain (2,000–3,000 microstrain), low frequency (1-3 Hz) events per activity unit, but to a persistent barrage of low strain, high frequency events (10-50 Hz), stemming from muscle contraction to retrain or maintain posture (Fritton *et al*, 2000). This might explain the bone mass accumulation in athletes playing sports like artistic gymnastics, tennis or hockey (Jones *et al*, 1977). Results from in vivo experiments using an animal model showed that the controlled repeated application of a force with a 1 Hz signal frequency at a strain of 250 microstrain over a daily loading period of 100 s could not maintain bone mass over an 8-week period while the same procedure with a 15Hz signal frequency stimulated substantial new bone formation (McLeod *et al*, 1990). It should be critically reviewed if the differences of the total energy exposed to the animals bone had the prime effect to tissue response and if the loading frequency had a minor effect to bone mass changes. A number of studies indicate that large intense challenges to the skeleton are generally presumed to be the most osteogenic. Brief exposure to mechanical signals of high frequency and low intensity has been shown to provide a significant anabolic stimulus to bone (Ozcivici *et al*, 2010). Such low intensity and high frequency stimuli are related to muscle contraction and therefore related to the active or bouncing loading in jumping, running and retaining posture and balance.

The review of the literature neither indicated that repetitive impact forces (mainly low frequency impact) in running are directly related to overuse or fatigue injuries of the lower limb nor supported that impact forces occurring in running or similar activities (e.g. impact aerobics) have an important or even an excessive osteogenic stimulus to bone. From the recent knowledge one can conclude that muscle contraction seems to play the outstanding role in maintaining and increasing bone mass and that the mechanical signals generated by the muscle forces are the most important anabolic agents in bone. The above discussed few high strain (2000–3000 microstrain), low frequency (1-3 Hz) loading events per activity unit in order to increase bone mass might not be applicable from running mechanics at low speed only.

Impact loading and response of cartilage: Some studies on articular cartilage response demonstrated negative effects of impact loading. However, in some cases, the forces applied were active instead of impact forces. Sometimes the stresses applied were much higher than those experienced in an athlete's knee during running and the used loading regimens were often rather severe (Radin *et al*, 1973). Bourne *et al* (2005) reported a decrease of cartilage cell viability when applying impact loading to an animal knee at higher energy and increasing loading repetitions. Thresholds in ultimate strain rate, impact stress and impact energy, which caused permanent damage to the structure of osteochondral plugs of bovine femora, have been reported by Verteramo and Seedhom (2007). A number of in vitro studies have investigated human cartilage mechanical properties of cartilage explants with confined (Jurvelin *et al*, 2007; Trepo *et al*, 2000) or unconfined compression (Julkunen *et al*, 2008) or indentation (Kiviranta *et al*, 2008). Due to the in vitro environment only limited conclusions can be derived from these reports in regards to the human articular cartilage properties in vivo. SHORT TERM RESPONSE: In vivo reconstruction using MRI imaging generated some interesting information of cartilage volume, thickness and deformation response to loading. Different mechanical loading patterns (e.g. walking, squatting, and cycling) lead to dose and site dependent knee joint cartilage deformation (Eckstein et al, 2005). The effect of running was most intensively studied and it was shown, that 30 minutes slow running decreased the femoral cartilage volume of 5.3% (medial) and 4.0% (lateral), whereas at the tibia only the cartilage volume of the lateral compartment was significantly decreased (Bookook et al, 2009). Impact type loading (jumps from 40 cm height) was related to a decrease of volume of 7% in the tibia (Eckstein et al 2006). Unfortunately the impact type of mechanical loading was neither controlled nor reported in this study. A controlled intervention study (Brüggemann et al 2011) reported a strong relation on cartilage volume decrease and the type of impact loading. High frequency impact loading (100 landings from 73 cm height) and low frequency impact loading (4300 footfalls in running) with the same total initial energy knee cartilage led to a higher cartilage volume decrease for the low frequency loading regime than for the high frequency with greatest effect at the tibia plateau. LONG TERM RESPONSE: Eckstein et al (2002) reported that opposite to bone and muscle cartilage thickness was not modulated in the subjects post natal by an increase of mechanical stimulation. But male and female athletes displayed larger joint surfaces than physically inactive controls, despite similar body dimensions. The long term response of articular cartilage has been described in a limited number of 18 subjects from an athletic population and 18 controls (Eckstein et al, 2002). The analyzed athletes were recruited from a population of athletes (triathletes) which never received "impact" loading (HFI) but repetitive "bounce" like loading (LFI loading) in running and active loading patterns in cycling and swimming. A recently published study (Brüggemann et al 2011) approached the question whether or not the cartilage has the potential to adapt to high frequency impact loading (HFI) in the long term by increasing its volume. The absolute values of the athletic (>10 years participation in HFI sports, n=10) and the non-athletic (n=14) sub-group have been compared and demonstrated no differences of cartilage volume in the analysed joint areas. Even when considering body mass and/or body heights non significant differences between the normalized volumes in all the cartilage plates have been found. These findings might reveal a general principle in the development and functional adaptation of diarthrodial joints, elucidating an important mechanism for reducing mechanical stress in biphasic cartilage layers.

SUMMARY AND CONCLUSION: High frequency loading at high loading amplitude is related to a high deformation velocity of the articular cartilage. This high velocity loading condition will attract the stiff elastic behaviour of the articular cartilage. The fast and small cartilage deformation at the collision of the joint partners might minimize the fluid flow and therefore the relative tissue movement. Local strain at the contact area should be increased. In summary, one can conclude that high frequency impact like loading is related to a more elastic and stiff behaviour of the articular cartilage and minimizes, due to the short loading period, the high loading rate and the related high deformation velocity, the potential of the tissue to deform (fluid flow) and to absorb energy. "Impact" loading in such sense (high frequency, high amplitude) should have the potential to increase the local strain and probably – if the contact energy applied is excessive – to reach the ultimate strain limit of the tissue. The data of absolute and normalized cartilage volume indicated no tissue adaptation associated with volume or thickness increase to mechanical loading in the long term. Articular cartilage of the human knee seems to be optimized in regard to load transmission, load distribution within the joint and in relation to tissue nutrition. From such a standpoint cartilage volume and therefore cartilage thickness should optimal and not maximal. The critical analysis of impact type loadings and their effect on bone and cartilage led to a more precise understanding of human impact loading. The term “bounce” type or low frequency impact loading allowed to increase the understanding of experimental results mostly performed on running and running related tissue response in the past. The recent experimental results provided some evidence on two complete different loading regimes related to different articular cartilage responses.The characteristics of the loading forces are related to the external physical conditions but might be modulated by the individual subjects with respect to muscle activation and/or co-contraction. “Impact” like loading pattern in regards to high frequency forces is strongly related to muscle forces and co-contraction. High amplitude loading is dependent from the initial energy of the entire body. Both, initial energy and muscle activation, give the potential to control the mechanical loading in a practical environment of physical activity and sports. The better control of mechanical loading seems to be the key to minimize tissue overuse and to optimize biological tissue adaptation. From the recent knowledge muscle contraction seems to play the leading role in maintaining and increasing bone mass because the mechanical signals generated by the muscle forces at a high frequency might be the most important anabolic stimuli in bone. The articular cartilage seems to fail in functional adaptation to loading in the long term. The increased understanding of the different tissue behaviour related to different mechanical loading during high or low frequency impacts offers an access to control tissue loading and to prevent overuse.

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