# BIOMECHANICAL AND BIOLOGICAL LIMITS IN ARTISTIC GYMNASTICS

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Artistic gymnastics increased excessively the difficulty of single elements and entire routines in the last decades. Biomechanical and biological factors related the performance enhancement indicate that the potential of the musculo-skeletal system seems to be close to the limits while the neural motor control systems have already achieved the ultimate tolerance limits. Strategies to ensure that the neural systems' stress stays below the critical limits are not well understood. A further increase of difficulty in the particular sport will increase the risk of failure of the biomechanical and biological systems. Acute and chronic severe tissue injuries are reported from male and female artistic gymnastics. In general mechanical loading of the musculoskeletal system is a prerequisite for morphological and functional adaptation of biological material. But there are indicators that stress and strain in artistic gymnastics increase to a level which exceed the mechanical limits of the individual structures. Artistic gymnastics seem to be close to the biomechanical and biological limits. A further increase of the difficulty in this sport and an increase of mechanical energy applied to the systems may lead to more frequent failures in both the biomechanical and the biological components.

**KEYWORDS:** Difficulties in gymnastics, acute and chronic tissue failure, spinal abnormalities, mechanical loading, morphological and functional adaptation.

**INTRODUCTION:** Artistic gymnastics is one of the most spectacular Olympic sports. The artistry and the skills performed by the gymnasts appear to be often close to the ultimate limits of the human body. Sometimes reported severe injuries lead to the assumption that the ultimate biomechanical and biological limits are achieved. Several papers report chronic injuries and spinal deformities of former gymnasts (Pollähne 1991) which seem to be related to the sport. Other epidemiological studies (Tertti et al. 1990) did not identify major differences in early tissue degeneration between gymnasts and non gymnasts. The technical requirements and the difficulties of the single skills and the entire routines in artistic gymnastics increased dramatically in the last thirty years. Recently one can observe a strong condensation of difficulties in the routines of males and females gymnasts which makes the sport extremely comprehensive. The speed of the development of more difficult elements is increasing. While in the Olympic cycle 1992 to 1996 thirty new elements were counted, twenty five new elements have been presented at the World Championships in 1997 (Fetzer 1997). An increase of difficulties is mainly a result of the rules in the specific sport; in artistic gymnastic the Code of Points. In addition to the rules the development of material and apparatus, the increased knowledge of training the athletes and probably an increased impact from science should influence this rapid development. The new elements are mainly developed by the addition of one more rotation to the somersaults or to the twists or to a modification of the body configuration during the difficult movement (tuck to pike, pike to straight). An increase in difficulties goes along with the demand for higher mechanical energy achieved. The higher mechanical energy for an element allows e.g. a higher flight and improves the flight time for the execution of the more difficult skills (e.g. straight body configuration instead of tuck). A higher angular momentum is the prerequisite for more somersaults and/or twists. Higher amounts of mechanical energy for the most attractive flights are related to higher energy when landing from the flight and increase biomechanical requirements for the biological structures involved. The higher demand on energy generation is related to a higher mechanical loading of the biological structures responsible for the force production, the force transmission to the skeleton and to the abutment. The higher mechanical energy for the skills is related to higher linear and rotational velocity of the entire body and its body segments which increase the stress of the biological systems for balance and motion control. Biological structures and systems have the potential for functional and morphological adaptation. The reported failures of the biological system of male and female gymnasts and the increasing frequency of mistakes during the routines in the competition as well as in training indicate the approach to the structural and functional limits of both the musculo-skeletal and the motion and balance control systems. On this background the paper will discuss the recent knowledge and the uncertainty on the biomechanical and the biological limits in artistic gymnastics. The focus is first on potential limits in performance enhancement and secondly on the limits in tissue tolerances.

**PERFORMANCE ENHANCEMENT:** The further enhancement of performance or the increase of difficulties in elite gymnastics should be limited by biomechanical and biological factors. Biomechanical factors are related to (a) the mechanical properties of the gymnasts' body segments (mass, moment of inertia), (b) the mechanical energy or the linear and angular impulses of the gymnast's body available for the specific skill (e.g. the initial mechanical energy at release for a flight element or a dismount), (c) the additional work done during the specific skill (e.g. the muscle work trough the hip and knee joints), and (d) the mechanical properties of the apparatus (e.g. the potential to store mechanical energy). Biological factors are (e) the potential of the muscle tendon units to generate mechanical energy, (f) the alignment of the muscle tendon units to the skeleton or the muscle tendon architecture (e.g. lever arm, penation angle of muscle fibers) , and (g) the potential of the neural control systems to withstand or tolerate time pressure and mechanical disturbance.

Research performed to affect the enhancement of the difficulty in a given sport and to identify the biomechanical and biological limits for a given skill or element may proceed following on a general pattern. Firstly, the factors which influence the particular skills or elements are studied. Secondly, attempts are made to understand the connection between these factors and the enhancement of the given or modified skill (from triple to quadruple somersault). Thirdly, attempts are made to influence the relevant factors to increase the difficulty of the element under study. Fourthly, evidence is provided to verify that the selected strategies in fact enhance the performance and are not counteracted or limited by the limitations of the biological factors (e) to (g). The first step is made by using experimental data and/or a theoretical approach; the second and the third step should use deterministic (e.g. multi body dynamics and computer simulation techniques) or more indeterministic approaches. The fourth step is made by using prospective epidemiological studies. However, different approaches may be used for the second and third steps. One possibility may be a mechanistic "cause-effect-approach", another one an "empirical approach". The following will primarily be focused on the cause-effect approach.

The approach is based on mechanistic assumptions which describe the factors and conditions of importance. Three factors determine whether a particular skill can increase the difficulty and enhance the total performance because of an increase of mechanical energy or the linear and angular impulses of the gymnast's body prior to the specific skill, the increase of additional work done during the specific skill or element, and the modification of the mechanical properties of the apparatus:

(1) The potential of the muscle tendon units of the given athlete to generate a higher amount of mechanical energy,

(2) the alignment of the muscle tendon units to the skeleton and the muscle tendon architecture, and

(3) the potential of the neural control systems to withstand or tolerate time pressure and mechanical disturbances.

While the factor alignment of the muscle tendon unit and muscle architecture should be assumed to be constant for given athlete the factors potential of the muscle tendon unit and potential of the neural control systems are of relevance for the further considerations.

In order to contribute to a performance enhancement it could be proposed that research in biomechanics should take a series of steps: (I) it should identify for each of particular skill and modification of the skill the necessary increase of the potential of the muscle tendon units and the additional loading of the neural control systems; (II) it should determine the critical limits of the loaded systems (muscle tendon units, neural control systems) and it should determine the additional load on the muscle tendon and the neural systems and compare it to the critical limits; (III) it should be determined the factors influencing the additional loading and develop strategies of ensuring that the load of the biological systems stay below the critical limits.

**(I) Increase of the potential of the muscle tendon units and the additional loading of the neural control system in a gymnastic element of higher difficulty**

The determination of the increased potential of the muscle tendon units may prove to be difficult in some cases. The determination reveals models to quantify or estimate the additional force potential which means models including muscles and tendons with it realistic mechanical properties. The additional stress on the neural systems should be estimated by a more indirect approach describing the modified time regimes for motion control and the increased segmental angular velocity. The accurate determination of the additional stress is a prerequisite for the successful application of the cause-effect approach. The methodological and technical problems suggest that there are cases where this approach is not possible. In some cases the additional potential needed for a modified skill at higher difficulty is estimated by the increase of the initial energy or the linear and angular momentum e.g. at release for a dismount or a flight element on the horizontal bar with regrasp (e.g. Knoll 1994). Other researchers used the net joint moments during the execution of a simulated movement with higher difficulty as an estimate for the increased or modified potential of the muscle tendon units. A good example for this approach is the simulation of the tuck quadruple backward somersault dismount from the high bar (Brüggemann and Arampatzis 1993) based on a measured release characteristics (height of center of mass, gymnast's linear and angular velocities) of a triple somersault of a given athlete. The time histories of the net joint moments of the hip and knee joints were calculated using a simulation (applying a multi body dynamic model) of the quadruple somersault's flight. The maximum net joint moments and the calculated necessary torque rates were than compared with the capacity of the subject under study to produce voluntarily joint torques at the knee and hip joints. The comparison indicated that the net moments as well as the torque rates for the quadruple somersault dismount were within the biological limits of the given athlete. It is remarkable that until now the quadruple somersault is not a frequently performed element in artistic gymnasts. The biomechanical requirements are within the limits, other factors may limit the realization. It is well known that the net joint moments are a rough estimate of the muscle potential and do not allow a precise prediction of realistic requirements of the muscle tendon units. The problem is increased when considering more precisely the two joint muscles driving the knee and the hip joints. Part of this problem will be overcome with increased sophistication in modeling allowing greater accuracy. However, there are still a number of situations where an accurate determination of the additional requirements of the muscle tendon complexes is not possible with adequate precision.

The determination of the additional stress on the *neural control systems* in a skill of higher difficulty is a highly demanding task. A more indirect estimation should be the angular velocity of the body segments and especially the head segment. Knoll et al. (2000) used the gymnast's angular momentum and the angular velocity (somersault and twists) as estimates for the loading of the neural control systems. An increase of difficulty is often related with higher initial energy and thus with a short preparation phase for the movement with the increased difficulty (e.g. contact time for the push off from the vaulting table). The decrease of the time for the production of additional energy and the sensitive tuning of the segments' motion (e.g. during the push off for 2 ½ postflight somersaults in vault) should be used another estimate for the additional loading of the motor control systems. In skills with higher difficulties (e.g. flights with regrasp in a pike instead of a tuck body configuration) the time for the preparation the following movement (e.g. the regrasp followed by the next flight element) will be decreased. This decrease is proposed to be used as an estimate for the additional neural loading. The determination of additional loading of the neural control system in skills with higher difficulties is not finally solved. Nowadays rough estimates allow a first inside view. More sophisticated diagnostic tools may modify the problem.

The accurate determination of the additional loading of the muscular and neural systems is a prerequisite for a successful application of the "cause-effect approach. The discussed problems suggest that there are cases and skills where this is not possible and, therefore, this approach may not be applicable.

**(II) Critical limits of the loaded systems (muscle tendon, neural control)**
The determination of the individual critical limits of the muscle tendon stems and the neural control systems may be considered an important part in the cause-effect approach. Mean critical muscle (80 – 110 N/cm2) and tendon forces or more precisely stresses (110 N/mm2) are reported, the in vivo determination of the ultimate stress for the given athlete with sufficient accuracy is still difficult with the currently available methods. In addition the determination of critical limits of the neural system is not sufficiently solved. Indirect estimates and more anecdotal observations in the gymnastics practice indicate a critical limit of $1300°s^{-1}$ of the angular velocity for somersaults and $2100°s^{-1}$ for twists (Knoll et al. 2000). These data are derived from observations of elite athletes in gymnastics, diving and figure skating. The figures showed no changes in the last twenty years, a fact which was used by the authors to interpret the values as critical limits.
Changes in the men's rings rules towards a strong emphasis of static strength elements led to muscle tendon loading for more difficult routines clearly above the actual critical limits. As a result one can observe a dramatic change in the body configuration of successful gymnasts on the rings: excessive increase of muscle mass at the shoulder girdle and the arms coupled with a decrease of muscle mass of the lower trunk and the lower extremities. The changes in the body configuration allow the athletes to perform on the rings within the changed critical limits of the muscular system. It is remarkably that those top performers on the rings are recently not longer physically prepared to compete successfully on the other apparatus. Evidence for this development can be taken from the results of the last European Championships in 2005: None of the finalists on the rings received a final at another apparatus. The top male athletes on rings changed their biological factors in a way that they are not any longer prepared to withstand the biomechanical and biological demands of the other gymnastics events like floor, vault, pommelhorse, parallel bars or high bar.
The obvious lack or the weakness of an accurate determination of critical limits for a given individual should be one reason for a more successful wider and broader application of the cause-effect approach in the area of performance enhance.

**(III) Factors influencing additional load and stress**
The knowledge of the factors influencing the additional load and/or stress and of the development of strategies to ensure that the increase loading of the muscular and neural systems stay below the critical limits may be considered as being major important for the possibility of a further increase of difficulties in gymnastics. If the factors are known, movement strategies or technical solutions can be developed for ensuring additional loading within the critical limits e.g. of the neural control systems (e.g. increase of CM's vertical release velocity for a dismount and decrease of maximum angular velocity during the flight). If known, appropriate strategies can be applied to modify the individual critical limits of both the muscular and the neural systems. While the potential of the muscle tendon system to adapt to additional mechanical stimuli is generally known the capacity of the motor control systems to respond to more intensive load is not very well understood. Some evidence for the potential of the neural control systems to respond to higher loading is given by the comparison of athletes with and without intensive experience in rotational movements (Stangl et al. 1997). However, the mechanisms and related concepts are not fully understood. In general the comparison technique in general and the knowledge of the factors determining the additional load offer approaches to select appropriate strategies and technical motor solutions to ensure that the additional load of the muscle-tendon system and the neural control system stay below the individual critical limits.
The cause-effect approach may be successfully applied if the estimates of additional muscular and neural loading in gymnastic elements with increased difficulties are compared for systematical changes of important variables.

If the knowledge of the factors determining the additional loading of both, the muscular and the neural system with increased difficulty in gymnastics, is not available as a prerequisite of the application of the cause-effect approach a more empirical approach should be applied.
The development in the increase of difficulty in gymnastics elements and skills gives some evidence that the biomechanical factors are close to its maximum. This leads to an increased loading not only to the muscle tendon system but also – and with a special emphasis – to an increased stress of the neural control systems. The development or more precisely the stagnation of tolerated maximum angular velocity (Knoll et al 2000) in gymnastics elements indicate that the biological limits in this area seems to be achieved. The reported biomechanical factors would physically allow skills with higher difficulty but the control systems are not capably to guaranty control and movement stability. A good indicator for this statement is that the triple backward somersault on the floor, which was shown to be biomechanically and practically possible, disappeared from the podium due to the fact that the lack of motion control led to too many mistakes and resulting reductions in points. The further condensation of the difficulties will increase the risk of loading the gymnasts above the critical limits especially in the balance and motion control modes. A modification or improvement of apparatus has the potential to affect the biomechanical factors through more efficient energy storage and re-utilation capacity. This may lead to higher energy for the flights and dismounts and thus higher demands for the muskulo-skeletal system when the landing from the flight and technically increased demands to the landing areas and mats.

**LIMITS IN TISSUE TOLERANCE:** The further increase of difficulties in elite gymnastics is related to higher mechanical energy and higher mechanical stress on the biological structures. This increasing mechanical loading impacts primarily (a) the most distal joints of the kinematic chain in contact with the abutment (with the hands/arms or the feet) and (b) the spinal structures. Due to the increased frequency of loading and the more condensed loading schedule one has to consider not only the ultimate tissue tolerances but also the modification of tissue tolerance limits in repeated loading regimes.
Research performed to affect the risk of a given sport and the frequency of acute and chronic overuse may proceed following a general pattern. Firstly, the facts which influence particular injury or failure are studied. Secondly, attempts are made to understand the connection between these factors and the injury or failure. Thirdly, attempts are made to influence the relevant factors to reduce the frequency of injuries, failures and risks. Fourthly, evidence is provided to verify that the selected strategies in fact reduce the frequency of injuries. Ideally, the first and the fourth step are made by using prospective epidemiological studies. However, different approaches may be used for the second and third steps.
Concerning the factors influencing a specific injury or tissue response three steps can contribute to solve the research question: (I) Identification of structures and tissues damaged by a single or repeated mechanical loading. (II) The critical tissue strength tolerances should be determined. (III) The mechanical load acting on the tissue in the specific situation of exercise should be quantified or estimated and compared with the critical limits. Based on the identification of potential critical loading in specific gymnastic skills and drills, factors influencing the mechanical loading should be identified and strategies developed to ensure that the mechanical stress stays below the critical limits.

**(I) Structures and tissues damaged by a single or repeated mechanical loading**
The most frequent damaged or injured structures in gymnastics are those of the lower extremities (ankle and knee joints). In men's gymnastics the frequency of the upper extremity injuries is close to the lower extremities. Especially the shoulder joints are affected in male gymnasts. Spinal injuries and back pain are reported in about 30% of male and female gymnasts.
Epidemiological studies suggest that gymnastics (Goldstein et al. 1990) may accelerate the degeneration of spinal structures. Sward et al. (1990b) e.g. investigated abnormalities of the thoracic-lumbar spine. The radiological findings indicate both direct traumatic changes as well as disturbed vertebral growth. Sward et al. (1990b) concluded that both the age at onset of

athletic activity and the degree of mechanical load on the skeleton are important factors in the development of these abnormalities. Some authors warned about overloading the spine by physical activity and sports in the adolescence (Micheli 1985). Other studies found no higher frequency in disc degeneration in young gymnasts than in controls (Terrti et al 1990). Only few findings of mechanically induced injuries of discs and vertebrae in gymnastics can be identified in the literature (Sward et al. 1990a); some recent cases indicate the potential of acute damage of cervical spine structures. A common fracture in young athletes is a vertebral endplate fracture which is a compression fracture due to the nucleus pulposus herniation into the vertebral body. The compressive strength of the disk is greater than that of the cartilagious endplate.

Injury can result from a single overload exceeding an individual tissue's maximum tolerance. Such a situation may lead to catastrophic spine injuries. The term catastrophic injury is defined as any injury incurred during participation in sport in which there is a permanent severe functional neurological disability (non fatal) or a transient but not permanent functional neurological (serious) disability. Catastrophic injuries are relatively seldom in artistic gymnastics but they occurred. Even if the relative numbers a small, the anecdotally summarized absolute number of cases increased over the last twenty years. Unfortunately no hard data on an international level are available at the moment. Incidents near to a catastrophic injury are reported and happened more frequently in the recent time when the difficulty in artistic gymnastics increased. Such incidents are also observed in major competitions.

A chronic injury is initiated by microscopic damage of the tissue's structure. Long term repeated loading can worsen the injury which eventually becomes macroscopic and/or results in tissue degeneration. Based on this definition a relationship between injuries and mechanical energy can be concluded. The principal relationship between mechanical energy and injury gives us reason to examine the causes of muscular-skeletal injury especially in sports where high amounts of mechanical energy and mechanical forces are a prerequisite for successful activity and performance enhancement. Increased difficulties will increase the repeated stress on the biological tissue.

**(II) Critical tissue strength tolerances**

The determination of the individual critical limits of a particular tissue is an important step in attempting to identify mechanical overload. Mean critical force or strength boundaries have been determined experimentally in cadaveric tissue experiments (Yamada 1970, Hutton and Adams 1982, Grenaidy et al. 1993). Callaghan and McGill (1994) showed in an in vitro study in animal models that the compressive tolerance of a porcine vertebra increased by 40% when the specimen was loaded in a pressurized wet fluid environment in comparison to the traditional testing procedure. In addition it was found that the critical limits are influenced by immobilization (Woo et al. 1984), inactivity (Brinckmann et al. 1989), age, skeletal maturity and other factors. The individual differences might exceed 100% if compared to the minimal values measured. The biological tissues have the capacity to adapt morphological and functional and to increase their strength and functional capacity. Brüggemann (2002) reported an increase in bone mass and endplate areas in young elite female gymnasts in response to mechanical loading in gymnastics. In addition young female gymnasts had a higher water content of the discs than matched paired non gymnasts. But the response to mechanical loading was shown to be highly individual.

The accurate determination of the critical limits of the endangered or damaged anatomical structure in vivo is a prerequisite for a successful application of a strong cause-effect approach. Although if the determination of the critical stress limits with sufficient accuracy is difficult and weak with the currently available methods the rough estimation of the range of tolerances may be primarily helpful in identifying most critical loading in gymnastics.

**(III) Mechanical loading**

The methods used to estimate the forces acting on internal structures of the locomotor system regularly consist of two steps. In the first step the resultant moments and forces in a joint are calculated using the inverse dynamic approach. When the resultant forces and moments at a given joint are known they have to be distributed to force-carrying structures in the vicinity of the joint. The different structures (e. g. muscles, ligaments, capsules) acting and transmitting force around a joint have an infinitive number of possibilities for producing a specific movement or the resultant moments. Mathematically this results in an indeterminate system of equations. To solve the indeterminate problem Nigg and Bobbert (1990) differentiated the reduction and addition strategies. The reduction strategy solves the problem by reducing the number of force carrying structures crossing a joint. The addition strategy adds equations based on physiological considerations or mathematical optimization techniques. A substantial number of different models to quantify or to estimate spinal load with various degrees of sophistication are currently used. The sensitivity and the numerical results of the models are strongly dependent on the model's strategy, the precision of the model input data (resultant moments and forces, anatomical data) and – using optimization strategies – the chosen cost function. From this it can be concluded that the determination of mechanical loads on internal structures should be used more as estimates than as absolute values. Even if the estimates do not provide absolute values of tissue load during gymnastics an estimation of the load for different skills, movements, manoeuvers and training drills is important for identifying substantial and critical activities in gymnastics. The prerequisites for such a comparison are the use of the same model with the same optimization cost function and sufficient individual anatomical data.

The major and most dramatic clinical and radiological findings in gymnastics concern the thoracic-lumbar junction and the lumbar spine. There is a controversy in the discussion about which skill or drill in gymnastics produces the highest loading in regard to the thoracic-lumbar spine. Simmelbauer (1992) discussed the fast changes between flexion and extention of the thoracic-lumbar junction during the swings on the rings and horizontal bar as a cause for the growth disturbances in the growing apophysis. Other authors considered the damage at the apophyses in gymnasts (e.g. Sward et al. 1990) as a flexion trauma and speculated that this could be caused by incorrect landing. This controversy led to the inclusion of gymnastic landings and long swings combined with dynamic flexion and extension of the thoracic-lumbar spine in this paper.

The compressive forces in landings are significantly ($p<0.01$) higher than e.g. in running and showed the highest amplitudes in all the studied skills. Landing induced compression forces of more than 30 times bodyweight. As expected the compression forces increase significantly ($p<0.05$) with increasing kinetic energy at touch-down. The shear forces were more or less constant. In addition to the protocol of spinal forces the forces of the trunk muscles were estimated: The forces of the ventral muscle groups do not vary with the height of the fall, but the muscle force of M. erector spinae increases significantly ($p<0.05$) with higher energy during the collision between the athlete and the ground.

Initial energy at touchdown, body position at landing and trunk's angular momentum prior to landing are shown to determine the compression (and shear) force at the thoracic-lumbar junction with landing. The effect of the landing surface in terms of landing mats demonstrates the comparison of the maximum compression and shear forces when landing on an original gymnastic mat and the mat with a supplementary mat on top.

The giant swings (e.g. in the scooped technique) on high bar and uneven bars, prior to dismount and flight elements with regrasp were taken as intuitive high loading demands for the spine. Compression and shear forces were calculated over the whole skills. The data demonstrate that the spinal loading is a compressive type loading during the whole drill that muscle forces are therefore higher than the inertial forces and that compression and shear forces are counter-intuitively low in comparison to the above presented activities. Health problems due to swings and giants should be explained by different overloading mechanisms than compression and shear loading to the vertebrae and discs. Hyperextension with a high tensile strain on the anterior vertebral ligament and high tensile stress on the insertion to the vertebra may explain the tissue failure.

When comparing different loading regimes which are combined with different injury frequencies and profiles of abnormalities one can identify remarkable differences in the loading strategies.

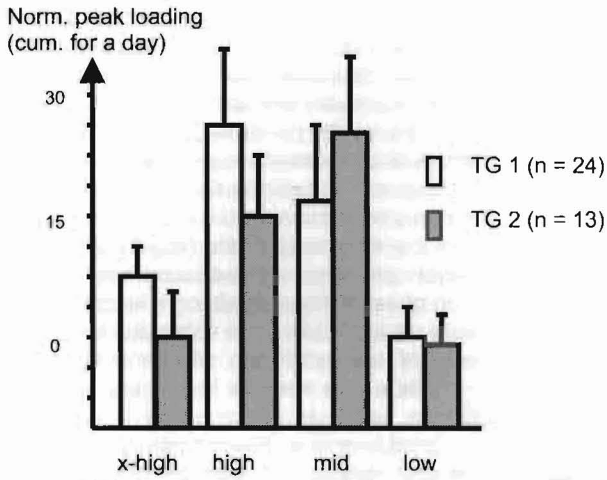


**Figure 1: Cumulated loading at the thoracic-lumbar junction (level Th12/L1) in two different training groups (elite female gymnasts) with different injury profiles.**

As shown in figure 1 in the training group 1 with a higher frequency of spinal deformities the extreme high loading is dominant whereas the moderate loading is more frequent in the group 2. Cumulative loading and different loading strategies seems to be a prerequisite for tissue response.

The mechanical load of the spine in gymnastics may reach or be close to the limits of tissue tolerances. The injury or the tissue damage will occur when these limits are exceeded in one traumatic failure or in repeated microfailures. Equipment, sport technique and training determine the mechanical load of the spinal structures induced by a specific regimen. A further increase of mechanical energy through an increase of difficulty in artistic gymnastics will approach the tissue loading to its ultimate limits and to breakdown. There are strong indicators that the loading in close to the tissue tolerance limits. There are a number of other skills in which - from a biomechanical point of view - critical techniques are being used. Examples are the hyperextension in front handspring vaults or landings from underrotated twisting somersaults. There is a need to evaluate such techniques, to develop alternatives, and perform epidemiological studies to prove sport techniques with less spinal loading.

**CONCLUSION:** Artistic gymnastics increased excessively the difficulty of single elements and entire routines in the last decades. Biomechanical and biological factors related the performance enhancement indicate that the potential of the musculo-skeletal system seems to be close to the limits while the neural motor control systems has already achieved the ultimate tolerance limits. Strategies to ensure that the neural systems' stress stays below the critical limits are not well understood and evaluated. A further increase of difficulty in the particular sport will increase the risk of failure of the biomechanical and biological systems. The approach of the neural control system to it's ultimate limits increased the risks to failure. Acute and chronic severe tissue responses reported from male and female artistic gymnastics may result in those failures. In general mechanical loading of the musculoskeletal system is a prerequisite for morphological and functional adaptation of biological material. But there are indicators that stress and strain in artistic gymnastics increased to a level which exceed the mechanical limits of the individual structures and the mechanical loading leads to tissue damage. Artistic gymnastics seem to be close to the biomechanical and biological limits.

A further increase of the difficulty demands in this particular sport and an increase of mechanical energy applied to the systems may lead to more frequent failures in both the biomechanical and the biological components.

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