JOINTS - NATURE'S HIGH-TECH? Biomechanical Methods, Instruments and Models for the Analysis of Load and Strain Imposed on Human Joints by Participation in Sport Activities.

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INTRODUCTION

Are joints nature's version of high-tech? Are they anatomical marvels moved and steadied by muscles, cartilage and tendons, incomparable in their precision and durability? Or are they - due to a phylogenetic development from quadrupedal to bipedal locomotion - to be viewed more as faulty constructions whose complicated mechanisms are highly injury-prone and whose structures fairly rapidly begin to show signs of wear and tear resulting from the stress of everyday use or of participation in sports?

This contribution will tackle this polarizing question. The dynamic aspects of the functional anatomy of the large joints (shoulder, elbow, wrist, hip, knee and ankle, as well as the vertebral column) are briefly presented, along with an overview of biomechanical methods, instruments and models for the analysis of loads and strains imposed on human joints by participation in sports.

About 350 million years ago the first sea creatures ventured up onto land, creeped on their fins and sensed for the first time - their own body weight. The bones and joints even of gigantic whales astonish us through their relative delicacy compared with terrestrial organisms which are passive objects of gravitational force. Bone- and cartilage linkages through so-called joints are an ancient patent recipe of nature, amazingly constructed, but also amazingly varied. Millions of years of testing ought to be enough time to create effective structures for adapting to the environment. In contrast to this enormous time span biomechanics tries to describe and understand biological systems, their function and behavior since just a few decades. Therefore, the accusation that biomechanics uses a reductionistic methodology is justified: the models which we develop to describe human motion sequences are still far from giving a good and sufficiently precise image of the incredibly complex structures and functional processes involved, and this is also the case with the analysis of joints.

The human life-expectancy has increased considerably in the last few decades and thus diseases of the bones and joints are becoming more common. To be sure, they seldom lead directly to death, but do play a major role as background illnesses. Already in 1936 Bätzner pointed out that non-physiological demands made on the human locomotive mechanism can lead to degenerative changes in joints, so-called osteoarthritis. Other authors have determined that no primary functio-genetic arthrosis is attributable to high-performance sports and endurance sports and that high-performance athletes need not fear a measurable deterioration through wear and tear of the locomotive apparatus, especially of the joints. The question of the tolerable load-level and demands, as well as the question of whether primary degenerative changes can arise in healthy tissue through moderate sports participation has up to now not been answered with any degree of certainty. However, it is unquestionable that sparing healthy joints through passivity and lack of movement harms them more than physiologically sensible (moderate) sport activity.

As recent statistical studies show, in the last few years complaints about injuries to the locomotive apparatus have increased considerably not only among high-performance athletes, but also among moderate sports participants. Among others, artificial outdoor turf and indoor playing surfaces, apparatuses, bad shoes and inadequate preventive measures are assumed to be the causes of overburdening of the lower extremities. What is feared is not sports injuries which occur through single or repeated trauma during a sport activity, but rather sports damage as a result of chronically influencing micro-trauma, overburdening, incorrect loading, or as a consequence of internal injuries, thus of the degeneration or wearing out of the tissue, arthrosis.

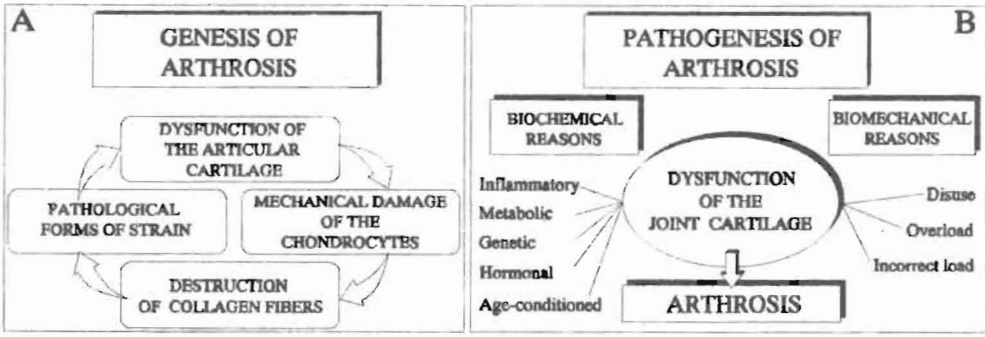

Fig. 1 Genesis and Pathogenesis of arthrosis (adapted from Feldmeier, 1988)

The pathogenesis of arthrosis is, however, so broad in extent, that certain knowledge of the dysfunction of the joint cartilage through over- and incorrect use in sports is very difficult to obtain, since joints are not only exposed to bio-mechanical stress, but can also be damaged in non-sport activities, as well as by biochemical hazards. For example, inflammation, metabolic, genetic, hormonal or age-conditioned factors can lead to the dysfunction of joint cartilage. Thus we cannot obtain an exact etiological or epidemiological classification of athletic joint injuries.

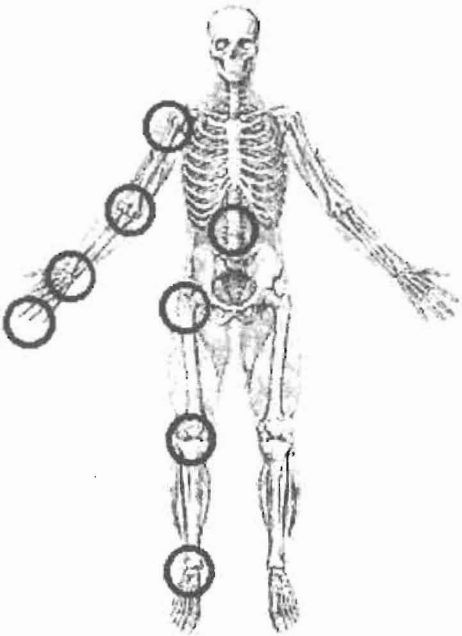

Fig. 2: Arthrosis deforms caused by sports
Shoulders: baseball, handball, swimming, wrestling, weightlifting;
Elbows: throwing, baseball, judo, boxing, karate;
Wrist: boxing, gymnastics;
Fingers: cricket, judo, climbing;
Hips: walking, running, hurdling;
Knee joints: rugby, football, soccer, skiing, weightlifting, basketball, baseball, hockey, judo;
Ankle joint: football, soccer, ballet, handball, volleyball, ice skating, hockey, baseball;
Vertebral column: wrestling, rowing, gymnastics, tumbling, bicycling, trampoline, javelin throwing, shot putting, diving, long jumping, high jumping, equestrian sports

Through an imbalance between the actual burdening and the load-bearing capacity of the hyaline cartilage tissue mechanical damage to chondrocytes (cartilage cells) can occur, whereby proteolytic enzymes are set free from the chondracytes and cause the dissolution of collagen fibers. This circulus vitiosus (Fig. 1a) can gradually wear out joint surfaces. An arthrosis deformans develops which is the most common disease of the human support and motion apparatus and today is at the top of the list of causes of disablement (Feldmeier 1988). Primary biomechanical causes play a major role in the pathogenesis of arthrosis in sports through the overburdening of joints (micro-traumatization of the cartilage), immobilization of joints and especially through incorrect burdening of joints (pressure and tension peaks on the cartilage). Preventive biomechanics has adopted the goal of analyzing, measuring and calculating the forces and torques which can under certain circumstances pathogenically affect the joints, in order to be able to derive from this knowledge and these results clues as to the burdening and demands made on human joints in sports activities, especially from the viewpoint of developing preventive measures.

METHODS

In order to be able to measure and calculate the burdening and demands made on joints in sport activities complex biomechanical research methods are drawn upon.

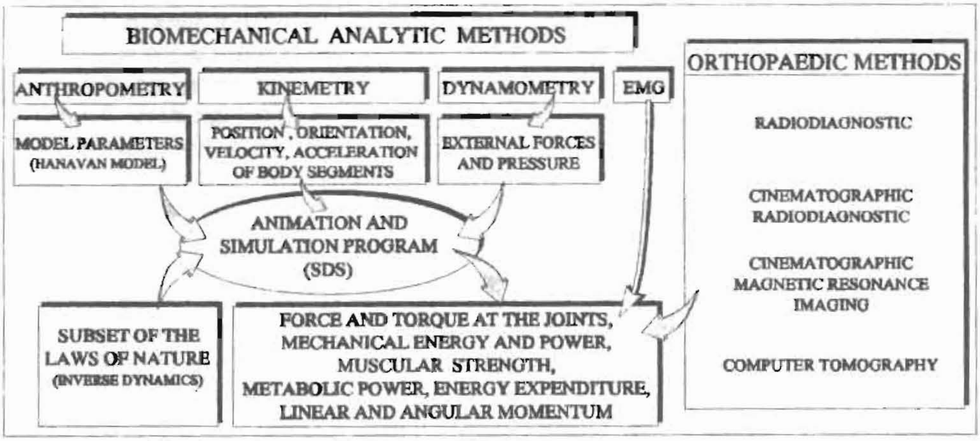

Fig. 3 Biomechanical analysis and orthopedic Methods

In Fig. 3 methods of biomechanical analysis are schematically represented which are employed by the Institute for Sports Science at the University of Konstanz, whereby the orthopedic methods especially support anthropometry. A multiplicity of different methods are known which are dealt with briefly in the lecture and can only be considered as examples.

It is very difficult to measure forces exerted on joints in vivo. Measurements with a telemetry system built into artificial hip replacement joints (Graichen, F.; Bergmann, G. 1991; Hodge, W. A. et al. 1986) provide information about the pressure exerted on human joint cartilage in vivo. Other procedures in vitro (Eckstein, F. et al. 1993) give information on contact surfaces and the distribution of pressures on joints. These results cannot be transferred without reservations to joint burdening in sports. We are therefore dependent on kinematic procedures, whereby biomechanical models form the basis for specific measurement and calculating methods (Olney, S.J./Winter, D. A. 1985; Nissell, R. et al. 1986; Ericson, M.O./Nisell, R. 1987; Ladin, Z./Wu, G. 1991; Scott, S.H./Winter, D. A. 1993; Li, J. et al. 1993; Lengsfeld, M. et al. 1994; Eng, J.J./Winter, D. A. 1995).

In 1990, we, at the University of Konstanz, began to develop an animation and simulation system. The whole system was constructed based on the Hanavan model and included the components for

- anthropometry: to establish individual references of the subjects in the computer database;
- kinematics: to work with the 3D-data of our digitizing system;
- display: to visualize the movements;
- general data output: to give all wanted parameters as functions of time; a subset of it can be seen in Fig. 3;
- calculation: the inverse dynamics and the simulation.

The first results were given in *The Rotational Ability of the Human Body* (Vieten, M. M. / Riehle, H., 1992a) and *Somersault-Twist Techniques in Sports - Trampolining* - (Vieten, M. M. / Riehle, H., 1992b). In 1993 the commercial software SDS of the French company Solid Dynamics replaced parts of our self-written program, the components kinematics, display, and output were substituted accordingly. This new software offers a general programming environment. Therefore, we are able to develop more refined anatomical models. An initial project dealt with the mechanics of the knee. To obtain exact measurements of the projection of joint axes on the skin we studied, based on the works of Menschik (1987) and Kahlfuß (1971), with the aid of nuclear magnetic resonance tomography and x-ray cinematography, the knee joints of 15 subjects in vivo and 3 joints in vitro, ankle joints of muscular cadavers. The results of these measurements made it possible to obtain precise anthropometric data in the framework of kinematographic motion analysis. Using as an example the knee joint, three different positions are shown as obtained using nuclear resonance tomography (positions 1, 8 and 16) and from computer analyses, whereby the origin coincides with the external marking on the knee joint for kinematographic analysis.

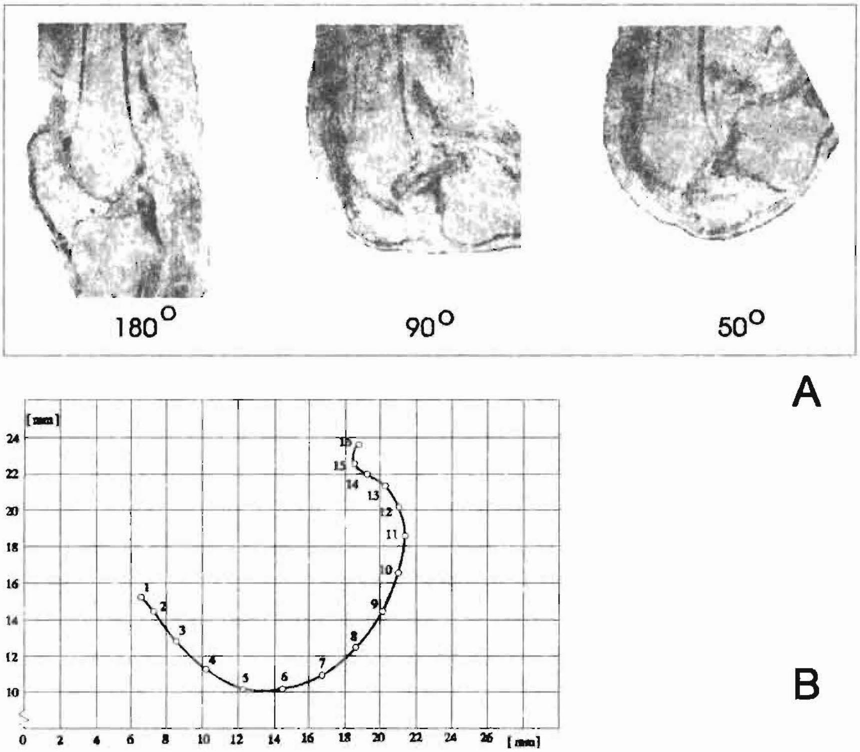

Fig. 4 Calculation of the momentary axis of rotation of the knee joint with the aid of nuclear magnetic resonance tomography
A: Nuclear magnetic resonance tomography, layer 16, positions 1, 8, 16
B: Gait pole curve according to the crucial ligament method

RESULTS

Biomechanical research

Our system for calculating the forces and torques of the joints in trampoline gymnastics needs, as input, the data of a digitizing system and the external forces with their points of application. Our Peak Performance system delivers all 3D-coordinates. Hereby, all velocities and accelerations are generated. The only external forces in trampolining are - neglecting air resistance - the forces on the feet during contact with the trampoline. Therefore, the angular momentum as well as the acceleration changes only during these phases. While being airborne the acceleration of the center of gravity is constant (g=-9.81 m/s). A measurement of the pressure on the soles of the feet gave us the correct points of application of the external forces. Pressure distribution measurements were carried out on the feet of the trampolinists. It was found that the pressure distribution on the front and back of the feet (Fig. 5a) gives rise to almost equal magnitudes of force on the same. These results were included in the model.

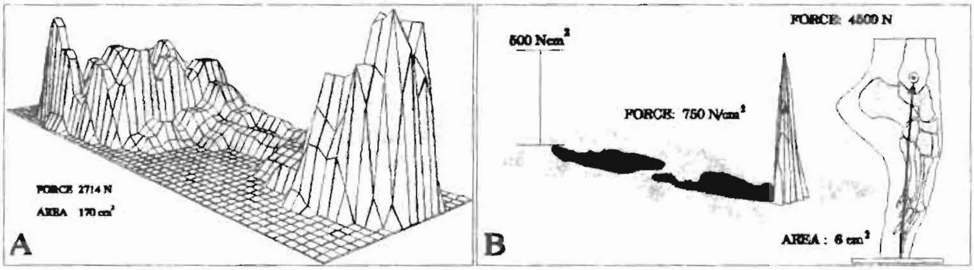

Fig. 5 Measurement of Pressure Distribution
A: Pressure distribution in the landing phase in trampoline gymnastics is computed to test the model for kinematic determination of forces and torques (Novel-Pedar system).
B: Pressure distribution with Emed pressure distribution measurement platform in ballet, including x-ray kinematographic study.

In earlier studies (Riehle, H. 1979; Hennig, E./Riehle, H. 1987) we determined that trampoline gymnastics is one of the types of sport whose athletes are exposed to extremely high levels of stress. Biomechanical analyses were made of high-performance trampolinists (4 world champions and 15 members of various national teams). Measurements of four KISTLER multi-component force measurement plates produced values between 13 and 16 times body weight, i.e., up to 16 kN were recorded. Fig. 7 details the sequence of forces in the landing phase in trampoline gymnastics. The values of the forces which are exerted on the vertebral column in take-off are 3,500 N on the vertical dimension (y-axis) and horizontally 1,500 N (Fig. 6). These magnitudes and functional dependencies, while recorded involving other subjects with almost identical anthropometry, are also found in results of our system using inverse dynamics (Vieten, M. M., 1996). With this input the following graphs were calculated.

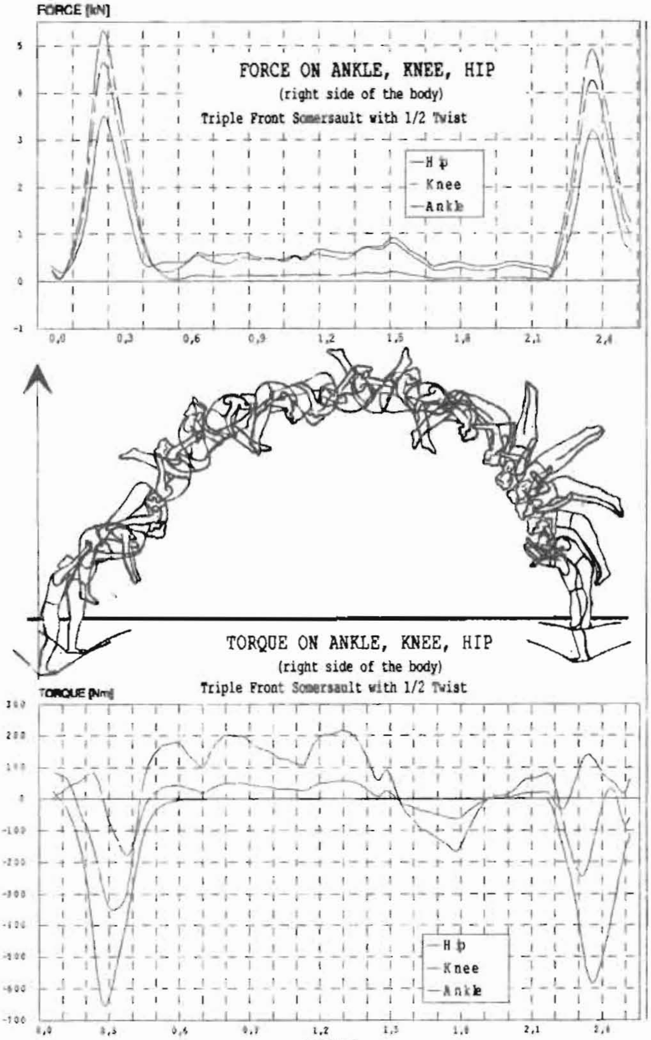

Fig. 6 The above graphics show the magnitude of the force, respectively the torque around the frontal axis of the hip, knee, and ankle joints during a triple somersault with ½ twist in trampolining. While the force is mainly balanced by the body's passive stabilizing system, the torque must be counter-balanced by muscle activity. During the somersault in the first half of the performance the hip torque (one leg) reaches a magnitude of up to 200 Nm (four times as much as the torque during a lever on the parallel bars).

Similar data of force and torque for the airborne phase of trampoline stands were reported by Vieten and Riehle (1995).

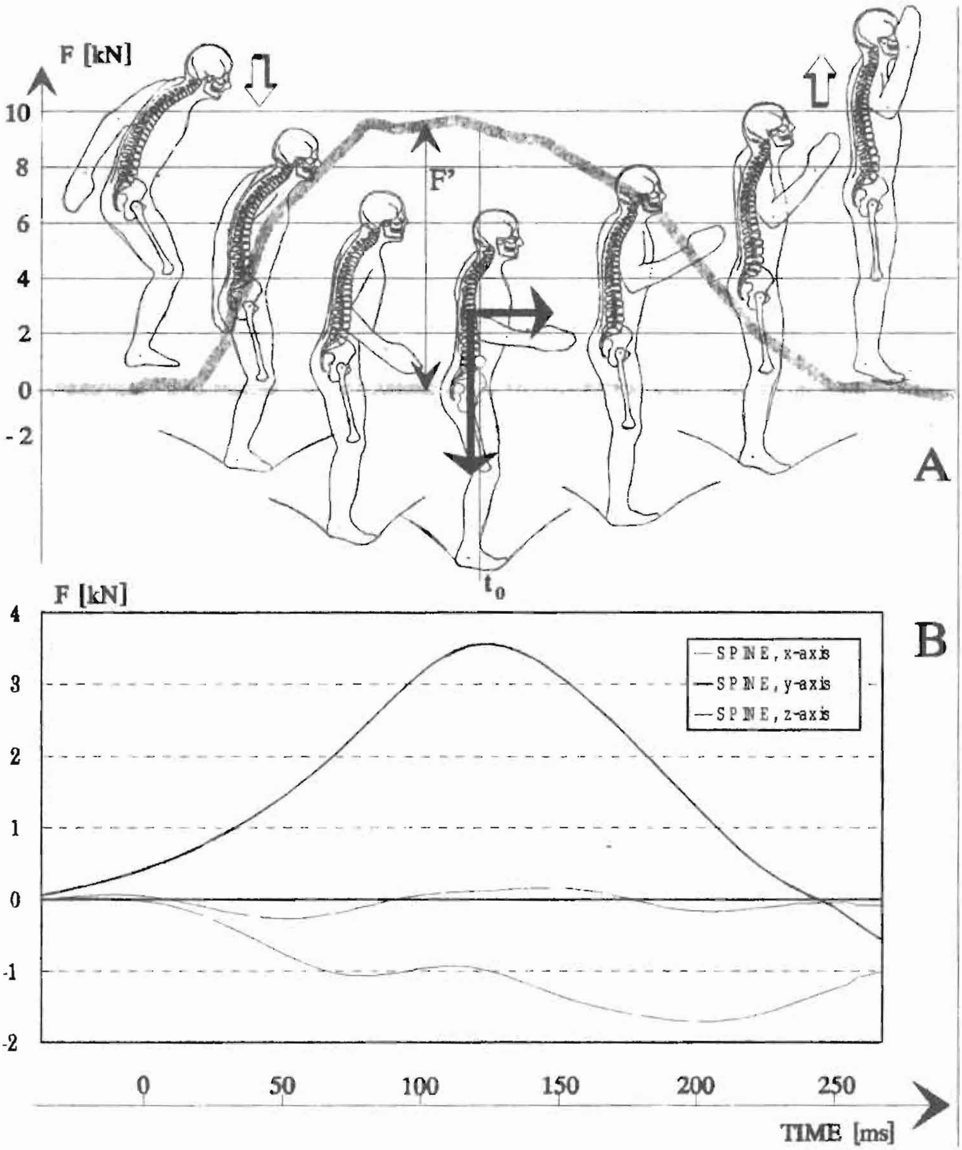

Fig. 7 Representation of forces exerted in the landing phase in trampoline gymnastics
A: Position of the vertebral column, F= 13.6 times the body weight, measured with Kistler force measuring plates
B: Kinematographically determined values with SDS

Orthopedic research

In addition, x-ray examinations were made to check the clinical results, that is, the influence of training on the trampoline on the vertebral columns of the trampoline gymnasts over a period of 8 years for 123 trampoline gymnasts and a control group (non-athletes) of 100 persons. Overall 2,850 x-rays were evaluated, whereby the sagittal pictures were used for the objective and quantitative determination of the prevalence of strain-induced damage to vertebra and intervertebral discs (Brinckmann, P. et al. 1993).

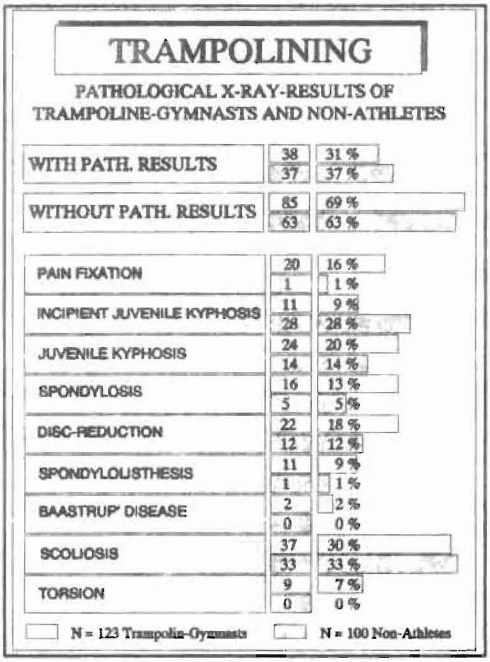

Fig. 8 X-ray-studies of Trampoline-gymnasts and a control group over a period of 8 years.

Fig. 8 indicates the results of the long-time x-ray studies, whereby no significant differences could be determined in the overall results between trampoline gymnasts and non-athletes. Merely the relatively high number of spondylolisthesis points to the high horizontal forces which are present in trampoline gymnastics. On the basis of these facts changes are suggested in the training procedure (e.g., special training of the trunk musculature), the technique of leaping and the elimination of specific leaps which strain the vertebral column along in the horizontal dimension as well as the wearing of a special waist-girdle to support the vertebral column and to reduce the horizontal components of acceleration, especially the lumbar spine. Follow-up studies of experimental subjects have shown that subsequent damage through trampoline gymnastics is not to be anticipated.

Kinematographic x-ray diagnostics were employed with 20 subjects (12 female ballet dancers and 8 sports students) dancing on points (Fig. 5b) and walking, while simultaneously measurements were made with Emed plates of the pressure distribution and arrangement of forces on the skeletal system and joints (ankle joints and joints in the foot base, mid-section of the foot and toes) under dynamic conditions. Similar studies were performed on 5 contortionists from the Mongolian state circus with the aim of making a movement analysis of extreme hyperextension mechanisms of the vertebral column. X-ray kinematographic pictures were made of hyperextension of the vertebral column (Fig. 9). The figure shows a lateral cross-section of a female contortionist balanced above a vertical bar. She supports herself on it, holding its rounded end firmly in her mouth (1). Her torso is arched over her head from the rear, and above her a second athlete does a handstand, balancing on her hips (2). Her legs are arched forward and balanced above and in front of her face. In B we see a lateral detail of the woman's vertebral column from A. In both cases clinical studies were made to determine whether possible pathological conditions were present as a result of daily training stress.

With the ballet dancers it was found that 4 subjects suffered from excessive strain on the talonavicular and dorsal cuneonavicular ligaments, and 2 subjects was suspected of having osteonecrosis of the intermediate coneiforme bone, which can also be related to the kinematographic results (x-ray and

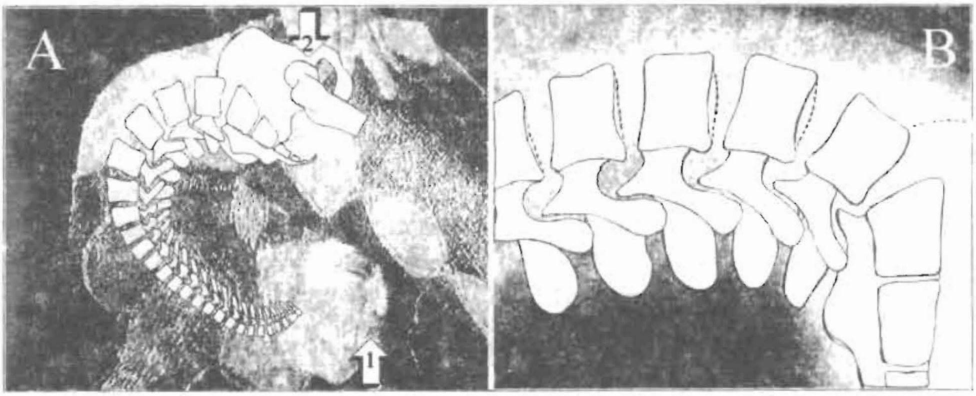

Fig. 9 X-ray joint kinematic movement analysis of contortionists
A: X-ray in hyperextension of the vertebral column (force transfer through the mouth (1) with additional strain on a gymnast doing a handstand (2)
B: X-ray kinematography in hyperextension position according to A

pressure distribution), since a „engaging" in this dancing on points especially burdens of the cuneonavicular joint. With studies of contortionists no pathological symptoms were found in the vertebral column, although the girls studied had trained up to 5 hours daily since childhood. The most extreme flexibility in these hyperextension mechanisms was measured in the hip joints and the segments between L5/S1 and the neck vertebra.

CONCLUSION

Biomechanical and orthopedic methods and studies of the strain imposed on and demands made on joints were presented using as examples ballet dancers, hyperextensionists and trampoline gymnasts. The existing data can be drawn upon as important sources of information to use in the development of training schedules for high-performance athletes and can also be very useful in working out preventive measures. Despite the possibility of such complex movement analyses, we are aware that our highly-technological world is still not in a position, even in the case of the apparently simple human anatomy, to obtain exact three-dimensional biokinetic and biodynamic data on the mechanics of joints and the burdening and demands made upon joints, such as occur in daily life and especially in the case of the most extreme athletic overload. Industrial scientists study metal- and plastic combinations in order to optimize the performance of artificial limbs. Through exact measurement of the limbs to be replaced using computer tomographic procedures they try to improve the adaptation of artificial joints. Yet even so, modern industry can still not offer an equally good substitute for healthy natural joints.

On one hand, joints are indeed nature's version of high-tech. If one looks at the mobility of professional gymnasts and the load-bearing capacity of healthy joints in sports, as in the example of the trampoline gymnasts and the contortionists used here, one would tend to give an unreservedly positive answer. However, on the other hand, if one examines the x-rays of patients suffering from hip-joint arthrosis for reasons of instance metabolic, genetic or hormonal diseases and the terribly painful movements of persons afflicted by arthritis, one would be only too happy to invent a better and more stable artificial joint. Could this be a faulty construction on the part of nature?

In all cases, we must learn to better understand the functionality of our locomotive apparatus! We must learn how to use this sophisticated instrument - the human body - correctly. This will in the future continue to be an important and necessary task of sports biomechanics.

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