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RECENT ADVANCES IN THE BIOMECHANICS OF SPORT INJURIES

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The causes of sports injuries are numerous and include such factors as the physical and psychological make-up of the athlete, his environment, training, playing field, coaching and the rules of the particular sport in which he is participating. Although our knowledge of the mechanism of sports injuries has been attained in the past through the use of observational and epidemiological data utilizing the deductive technique, we are now able to gain much information from inductive studies which depend upon scientific measurement and experimentation. Methodology has been discussed by *Groh & Baumann* (1971).

The tools of Biomechanics are useful in studying many of the factors which are important to sports injuries. An injury is the result of tissue trauma. Questions which must be answered are:

What are the stress, strain and energy levels that cannot be exceeded if injury is to be prevented?
What are the structural loads that result in tissue tolerance being exceeded?
What is the effect of motion on structural loading?
How may the effects of forces on the tissues be modified through training, technique and protective equipment?

In this paper we have summarized recent experimental knowledge which has clinical importance in the prevention and treatment of sports injuries and which is solidly based on Biomechanics data.

Biomechanics is a study of force and motion and the inter-relationships between them, including control mechanisms. Our activities of

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daily living depend on our ability to move; in the case of sports activities, rapid coordinated and strong movements are necessary. These movements in turn depend on our capabilities for producing muscle forces that can move the bones making up the joints.

The muscular, gravitational and ligamentous forces in our body have both internal and external effects. The external effect of a force on a body is to cause an acceleration of the body. In the case of a tennis player, muscle forces are used to impart an acceleration to the racket. The racket then imparts an acceleration to the ball, producing the velocity necessary to carry it over the net. There is also an internal effect which causes a state of strain in the body, that is, it effects a change of shape in the body. As the racket strikes the ball, the ball is compressed. Whether or not this state of strain will cause permanent damage to the structure depends upon its particular material properties.

In applying biomechanical analysis to sports injuries, one must constantly keep in mind this inter-relationship between force and motion. The science of biomechanics provides exact ways of measuring the forces and motion and allows one to determine the effects of forces on the tissues. It also allows one to understand the injury mechanism and possible injury preventative measures.

Mechanical properties of locomotor tissues

The ligamentous, tendinous, muscular, cartilaginous and bony tissues that make up the locomotor apparatus demonstrate complex mechanical properties including time-dependent viscoelastic behaviour, anisotropy, and ageing effects. The basic data to be determined inculde the yield and ultimate stress and strain, energy to failure, and moduli of rigidity and elasticity at realistic strain and load rates. With these data predictive mechanical and mathematical models of structural behaviour may be made.

Ligament

Noyes et al. (1974) noted that the anterior cruciate ligament is strain rate sensitive in primates. Tension failure occurred at a higher load, elongation and energy absorption at a fast rate of deformation than at a slow rate. The site of failure was also influenced by the loading rate. At the slow deformation rate, the bony insertion of the ligament was the weakest component and a tibial spine avulsion fracture resulted. At the fast deformation rate, which more closely approximated physiological loading conditions, there was an increased frequency of ligamentous failure. This suggests that with the increase in deformation rates, the strength of the bone increased faster than did the strength of the ligament. The authors also noted that in their experiments the ligaments elongated approximately 57 per cent prior to failure. They also noted, however, that the visual determination of continuity of a ligament often gave an inadequate determination of the extent of ligamentous disruption. A ligament which appears clinically intact may have undergone extensive internal failure or have internal damage to its blood vessels.

In a further series of experiments, Noyes et al. (1974) studied the effect of immobilization on the strength of the anterior cruciate ligament. Primate knees were immobilized for 8 weeks, following which the strength of the anterior cruciate bone-ligament-bone preparation was determined. There was a significant decrease in maximum failure load and energy absorption to failure and an increase in ligament extensibility (Figure 1).

After 20 weeks of resumed activity, there was only partial recovery in ligament strength. A voluntary isotonic exercise program during limb immobilization did not prevent disuse-induced changes in the ligament failure properties. Applications of these results suggest that following relative or complete immobilization, a longer period of time

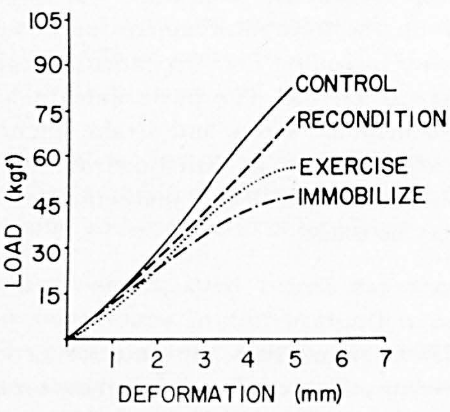

Figure 1. Load-deformation curves of ligament behaviour in primates. A significant decrease in stiffness (slope of the load-deformation curve) is seen in the exercised and immobilized groups. Partial recovery occurred at 20 weeks. (After Noyes et al. (1974) Biomechanics of ligament failure. J. Bone Jt Surg. **56**-*A, 1406–1418.)*

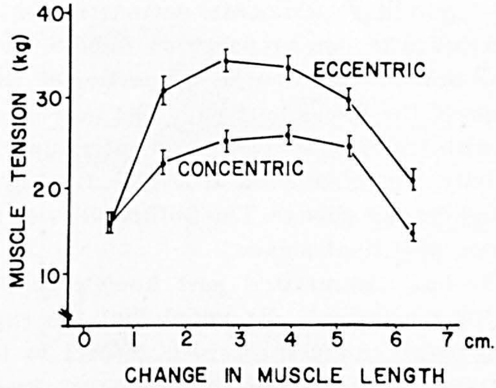

Figure 2. The length-tension relationship for the elbow flexor muscles in eccentric and concentric work. Velocity 0.8 cm/sec. (After Komi, P. V. (1973) Medicine and Sport, Biomechanics III, *224–229.)*

than is commonly realized may be required before the functional capacity of a ligament returns to normal.

Laros & Tipton (1971) studied the force required to rupture or avulse the medial collateral ligament in dogs after various levels of activity. In terms of body weight, there was a difference between caged animals which required a force of 2.8 times body weight and exercised animals which required a force of 3.5 times body weight to separate the ligament. They noted in histological preparations that periosteal resorption about the ligamentous insertion was found in both caged and immobilized animals. Increased mechanical strength of ligament after conditioning is of considerable interest in terms of athletic injury.

Muscle and tendon

Studies which are important in an understanding of the muscle and tendon lesions have been reported by Komi (1973), who used a dynamometer to measure the force-velocity relationship of the forearm extensor and flexor groups. The maximum tension of the forearm flexors was always greater in eccentric than in concentric contractions (Figure 2). This phenomenon of muscle behaviour is influenced by the velocity of contraction. With increasing velocity the maximum eccentric tension at each muscle length increases and the concentric force decreases. This type of information is important in understanding such diverse injuries as high jumper's knee, rupture of the Achilles tendon and avulsion fractures.

Viidik (1969) reported experiments demonstrating the effects of training on an Achilles tendon preparation. Rabibts were trained in a running machine and the mechanical properties of the tendon were studied. The slope of the linear portion of the load-deformation curve became steeper with training, indicating an increasing stiffness in the tendon with activity. The elongation at failure, the failure energy and the maximum load did not change. The failure site was the insertion of the Achilles tendon at the calcaneus.

Barfred (1973) has summarized past knowledge and added new information in his monograph. He noted that the rupture limit for muscle has been poorly understood with respect to tensile strength and to elongation and that these failure limits must depend on the state of contraction of the muscle. The maximum isometric muscle force for man was stated by Buchthal & Schmalbruch (1970) to be 5–6 kp/cm^2. Barfred's experiments were performed by quick elongation of stimulated muscle tendon units utilizing a rat limb preparation. Ruptures were noted at varying sites in the muscle-tendon preparation. The frequency of tendon rupture was highest after a period of inactivity. The risk of tendon rupture increased when the muscle was exhausted. The elongation at rupture always exceeded the muscle-tendon length. The tensile strength and elongation at rupture limit were least in the inactivity group. The muscle which could develop the greatest force also had a greater separation force than the tendon, especially if it was contracted during the rupture experiment. Elongation of the unit at failure was greater when the experiment was performed with an uncontracted muscle.

Cartilage

Freeman (1973) has summarized current knowledge of the mechanical properties of joint cartilage, restating the two-stage compressive deformation phenomenon noted by Hirsch (1944). An instantaneous deformation occurs as load is applied. Due to creep, continuous deformation occurs as the load is allowed to remain. Most likely this phenomenon is related to the flow of water through the matrix. An important finding was that the mechanical properties of cartilage differ in different anatomical locations. These results reflect that the strength and stiffness of cartilage are strongly related to the extent to which the collagen fibres are oriented parallel to the direction of tension. The maximum failure stress recorded for cartilage was 348 kg/cm^2 for a parallelly oriented surface layer and the minimum failure

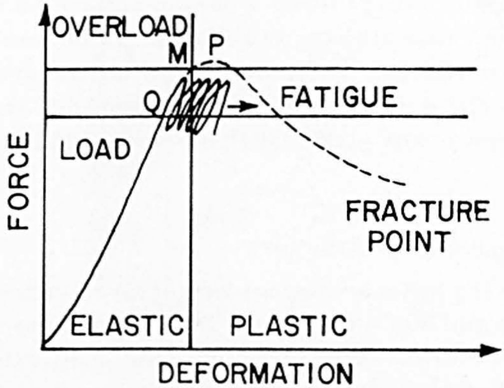

Figure 3. Cyclical loading and unloading in the fatigue zone, a slow bone deformation is observed progressing to the plastic phase. (After Chamay, A. (1970) Mechanical and morphological aspects of experimental overload and fatigue in bone. J. Biomech. **3**, 263–270.)

stress for a visually normal joint was 40 kg/cm². The exact relationship of load attenuating capacity and energy absorption ability of articular cartilage in response to athletic activities is still not clear, because the magnitude and distribution of the forces applied to cartilage are unknown.

Bone

Burstein et al. (1973) have demonstrated that bone is not brittle but, on the contrary, may undergo large plastic deformations. This plastic yielding in tension acts to enhance the strength of the whole bone due to the "plastic hinge" effect. Chamay (1970) has noted the presence of shear failure in bone loaded in compression (Figure 3). This fact is of the utmost importance in considering bone remodelling and the presence of fatigue fractures. Frankel (1972) has presented a theory of fatigue fractures in the athlete which is based on the fact that muscle fatigue leads to abnormal bone loading conditions which induce altered states of stress and strain in the bones. This leads either to a tension crack or to shear failure in compression. A fatigue failure in an athlete occurs because bone fails as it is loaded in the plastic region at a rate exceeding the normal rate of the bone repair. A knowledge of the mechanical properties of the bone tissue and its response to load is necessary if one wishes to understand the mechanism and prevention of fatigue failure.

Nilsson & Westlin (1971) using a photon-absorption method studied bone density in 64 male athletes and compared this result to 39 healthy age-matched non-athletes. The athletes had significantly higher bone density in the distal end of the femur than did the non-athletes. Significant evidence was produced that sports activity enhanced bone density.

Mechanical properties of structures

This includes the behaviour under load of structures such as the long bones, the spine and individual joints. Data acquisition includes experimentation with clinical load directions and load rates. Data to be recorded include load-deflection relationships, energy absorption characteristics of the structures and failure modes.

Spine

Markolf (1972) studied fresh human segments in order to measure the deformation in response to various types of movements. He noted non-linearity of the moment deformation curves with increasing stiffness as deformation increased. Torsional stiffness showed a marked change at the T-11/T-12 segment and he hypothesized that this discontinuity represented a site of structural weakness for torsional stress to the spinal column. He noted that the intervertebral disc was 1–1/2 to 3 times stiffer in compression than in tension.

Farfan et al. (1970) have made the important observation that torsional loading was responsible for intra-discal failure and that *in vivo* disc degeneration was due to imposed torsional strains rather than to compressive loads. Nachemson & Elfstrom (1970) have measured intra-vital pressures in the lumbar disc during common movements and exercises.

Skull

Radiotelemetry was used by Reid et al. (1974) to study the acceleration peaks resulting from impacts to the head from football contact. The peak ranged from 40 to 530 G's, while the duration was from 20 to 420 milliseconds. He noted that the neuromuscular response to the athlete was such that the head was positioned to cause the blow to glance off and allow the smooth hard exterior of the shell of the helmet to deflect the blow.

Ommaya et al. (1973) studied cerebral concussion in the chimpanzee

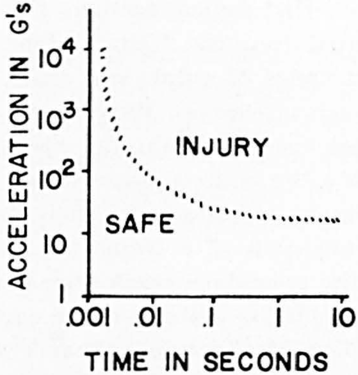

Figure 4. Relation between acceleration and time required to produce human injury. Note that high acceleration can be endured for only short lengths of time without trauma, while lower acceleration can safely last much longer. (Modified from Lissner et al. (1960) Acceleration and intracranial pressure changes. Surg. Gynec. Obstet. **111**, 329–338.)

following angular acceleration of the head and neck. They noted that when the head experienced an angular velocity exceeding 70 to 100 rad/sec, irrespective of how far the head was allowed to rotate, concussion was produced. Shear stresses and strains produced by the inertial loading produced the brain lesions. There is a strong relationship between peak acceleration, duration of acceleration and injury as noted in Figure 4 (Lissner 1960). These studies demonstrate that cerebral damage can occur without a direct blow being delivered to the skull.

Schmid et al. (1968) studied the efficiency of headgear in prevention of head injury during boxing and ascertained that the use of headgear reduces the acceleration by about 15–25 per cent, that is, acceleration of 175 m/sec^2 with headgear and 250 m/sec^2 without headgear. After the introduction of headgear, only 0.8 per cent of contests ended in a knockout, while formerly it used to be 3–4 per cent. Peak force with different sizes of gloves was further investigated by Unterharnscheidt (1972). Use of 6–0z. gloves could result in head acceleration of more than 100 G's. Peak force obtained with 6–oz. gloves was 2.7 times greater than that obtained with 16–oz. gloves.

Epiphyseal plate

Bright et al. (1974) reported studies of tests of the proximal tibial epiphysis of young rats. They noted that the epiphyseal plate possessed visco-elastic properties. Histological sections through the bones tested to failure demonstrated that the failure plane took a varied path through the different zones of epiphyseal plate. When the structure was loaded with a load which was 50 per cent of that which would cause failure, internal cracks within the epiphyseal plate are seen in the areas exposed to the highest shear stress. If the load was then released, the shear cracks remained and their presence weakened the plate for further application of a transverse load. If the force was allowed to increase, the secondary crack then became the propagating crack and passed through the plate to cause cartliage failure. Should human epiphyseal plate also develop shear cracks with subcritical loading, these experimental findings would help to explain the observed clinical symptomatology related to growth plate injury without radiological confirmation of disruption.

Kinematics and kinetics

This scientific study of motion (kinematics) such as kicking and throwing is performed to develop an understanding of the linear and angular displacements, velocities and accelerations that the structures undergo during sports activities.

From the acceleration data the loads on the structures can be calculated using the Newtonian laws:

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$
$$\text{Torque} = \text{Mass moment of inertia} \times \text{Acceleration}$$

Since energy is transformed constantly during sports activity, an understanding of energy transfers from the potential to the kinetic to the strain form is of value. When strain energy is allowed to reach certain levels, failure of the structure occurs depending upon the particular mechanical behaviour of the structure and its component tissues.

Kicking

Frankel & Burstein (1970) have analyzed the forces in punting a football and noted that for a maximal effort in punting, the force developed by the quadriceps tendon was approximately 3 times body weight. Youm & Huang (1973) have developed a computer program for studying simulated kicking.

Throwing

Using motion picture analysis, Tullos & King (1973) studied the mechanism of pitching in baseball. Their data support the fact that the highest acceleration force occurs at the beginning of throwing. The authors note that at the beginning of the acceleration phase, there is a valgus stress on the lateral side of the joint which may be responsible for the capitellar injuries noted in the elbow.

Jumping

Ramey (1970) utilized a force plate to determine the force-time relationships during the running long jump. His findings show that the maximal vertical force exerted at take-off is not the sole important parameter but that a combination of force, impulse and the mass of the athlete were primary factors in the ability to perform the long jump. He also demonstrated that the horizontal forces that exist at take-off act to decrease the horizontal take-off velocity.

Gombac (1971) studied the mechanics of take-off in the high jump. He noted that the vertical force on the ground exceeded 350 kg. He divided the take-off into three phases:

Leg placing -- It was during this phase that force against the ground was at the maximum.

Amortization -- A firm base of support of the whole foot was established. During this period of time, knee flexion took place so that the observed ground reaction force decreased to 100–150 kg.

The third phase was *active take-off*. There was an increase in vertical force. Amortization phase may be of great importance in the production of "high jumper's knee" in that the knee flexes under the control of very strong quadriceps forces, producing peak forces on the patellar tendon and its attachments.

The knee joint

The knee joint is the area on which the most intensive studies have been performed. Much good data now exist on the loads of the joint, the strength of the structures and tissues, and the mechanism of injury.

Great emphasis has been given to studies of the knee joint due to the many injuries encountered. The forces acting on the knee joint have been analyzed by Lindahl et al. (1969). They noted that the mean force exerted by the quadriceps was 520 kgf, which was equivalent to a force of 2.9 kgf/cm^2 of muscle cross-section. The muscle force exerted by the quadriceps in extension of the knee was determined in healthy males and found to vary with the position of the knee. The maximum moment of 2300 kgf-cm was recorded at 60–75 degrees of flexion.

Reilly & Martens (1972) studied the quadriceps muscle force and the patello-femoral joint force for various activities. The patello-femoral reaction force was at a maximum at 30–40 degrees of flexion. During deep knee bending the patello-tendon force reached a force of 7.6 times body weight. For stair climbing and descending, the force attained a level of 3.3 times body weight, which is almost seven times the force reaction found during normal walking and explains why patients with patello-femoral derangements experience more pain while climbing stairs. Quadriceps exercise performed by extending the knee from 90 degrees against the resistance of a boot weighing 9 kg yielded a patello-femoral force of 1.4 times body weight, explaining why some patients complain of retropatellar pain during the exercise. A straight leg raising exercise of similar weight produced a patello-femoral force of only 0.5 times body weight.

Instability of the knee is an important clinical finding. Experimental production of injuries resulting in instability has been performed by Kennedy & Fowler (1971) on a knee loading apparatus. Different combinations of forces and varying speeds were applied to cadaver knees. In the case of abduction and external rotation forces, the ligaments rupture in the following order: medial capsular ligament, tibial collateral ligament and finally the anterior cruciate ligament.

When the knee was placed in a position of 90 degrees of flexion, 30 degrees of external rotation could be produced without injury. At between 40 and 50 degrees of external rotation the tibial collateral ligament was found to be intact in the presence of a ruptured capsular ligament. With disruption of the medial capsular ligament, the usual clinical abduction tests failed to reveal gross medial laxity despite the obvious damage. When further external rotation combined with abduction was applied, damage to the tibial collateral ligaments was evident, but no damage to the anterior cruciate ligament occurred until the tibial collateral ligament had ruptured.

Alm et al. (1974) reported experiments on the tensile strength of the anterior cruciate ligament using a dog preparation. In 94 per cent of the tests ruptures occurred in the mid-part of the ligament. They noted that rotation of the tibia of an intact knee in man was considerable with the knee in semiflexion. The results of their study suggested that trauma causing rotation of the tibia decreases the tensile strength of the anterior cruciate ligament and increases the risk of rupture. Kennedy et al. (1974) stated that tension of the anterior cruciate ligament was greatest in full extension and in 5–20 degrees of flexion. The ligament was almost relaxed between 40 and 50 degrees and gradually became tauter as flexion increased to 70–90 degrees. They stated that isolated tears of the anterior cruciate ligament occur as a result of internal-rotation displacement of the tibia in relation to the femur.

Quasi-quantitative tension studies of the anterior and posterior cruciate ligaments of human cadaveric knee during various degrees of flexion were performed by Detenbeck (1974). He found that tension of the anterior cruciate ligament decreases progressively with knee flexion, and that of the posterior cruciate ligament decreases with initial knee flexion, but beyond 30 degrees, it increases progressively. Maximum combined cruciate tension is least between 30 and 60 degrees of knee flexion. The posterior cruciate ligament appears to guide the screw-home mechanism or internal rotation of the femur during terminal extension of the knee while the anterior cruciate ligament stabilizes the lateral femoral condyle on the tibia.

Warren et al. (1974) studied the function of the ligaments along the medial side of the knee. They concluded that the long fibres of the superficial medial collateral ligament are the primary stabilizer against valgus and rotatory loading. The long fibre as a functional unit has a complex pattern in which the anterior-most fibres tighten as the knee flexes from the position of extension, and simultaneously the fibres just posterior to them slacken. The long fibres arise from a critical point on the medial femoral condyle relative to the instant centres of rotation such that the anterior border is kept under tension from full extension to 90 degrees of flexion. Cutting the deep ligament and the posterior capsule produces almost no change in joint opening under valgus load if the long fibres are intact. Great valgus instability resulted from dividing the long fibres.

When a specific sports injury is encountered, a logical schema must be developed to analyse it fully. One must not forget the elements of control which are reflected in skill, trainability and performance and which may be strongly under the control of emotional forces and may decay with age.

The various protective devices may also be studied in a manner similar to the locomotor tissues and structures. Devices which are used to enhance ability such as shoe cleats and ski boots must also be analysed for their effect on structural loading and kinematics. Newer playing surfaces developed during the past few years to overcome the problems of maintaining turf also change the quality and quantity of the ground and environmental reactive forces.

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