3 Biomechanics of Musculoskeletal Injuries

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3.1 Introduction

Musculoskeletal injury is one of the most common reasons for days off work and reduced activity with approximately 126.6 million patients affected in the United States on an annual basis (Source: American Academy of Orthopaedic Surgeons, 2016). This has a significant impact on work-related productivity, quality of life, and health expenditure in corresponding health-care systems.

While there are many modalities available to treat MSK injury of varying kinds, one of the most effective methods of treatment is injury prevention. In an effort to address these injuries, it is of paramount importance to understand the biomechanical principals behind the injury, to enable an effective treatment or prevention strategy to be implemented.

This chapter will focus on providing an overview of the pertinent biomechanical principals behind MSK injury. An overview of tissue-specific biomechanical properties will also be provided, with these terms and principals then illustrated in sport-specific injury scenarios and mechanisms.

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3.2 Biomechanical Principals Relating to MSK Injury

When considering the mechanism of injury, it is important to understand the forces acting on the body and how they may affect the different tissues. The term ***kinematics*** describes the motion of body segments, while ***kinetics*** deals with a description of the forces that produce the specific motions [1].

When considering sports injuries, there are a number of simple units of measurement that must be taken into consideration to determine the magnitude of force acting on individuals. One such key measure is ***mass***. Mass is a measure of ***inertia***, being the property of an object to resist the changes in motion that affect it. A running back in American football, for example, must

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overcome inertia to start running; but his mass will also make it more challenging for him to be stopped. ***Weight***, on the other hand, is the force of gravity acting on an object.

In dynamic situations such as sports, ***Newton's laws of motion*** is important to understand, when considering how forces are acting on objects and, of course, participants or subjects in a game [2].

- ***Newton's first law*** states that a body continues in a state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon in.
- ***Newton's second law*** tells us that the change in motion of an object is proportional to the force impressed and is made in the direction of the straight line in which it is impressed. This law essentially describes acceleration, which is derived from length, time, and mass.
- ***Newton's third law*** of motion states that to every action, there is an equal and opposite reaction. This means that when the running back collides with the linebacker, the force of impact will be felt similarly on both players.

Stress and strain: ***Stress*** is defined as the force applied to an object divided by the cross-sectional area of the surface onto which the force is applied. There are three principal stresses that act on a body [2]:

1. ***Tension***—Tensile stress is that which occurs as a result of force that pulls apart molecules that bond the structure together. A lateral blow to the knee in soccer will result in tensile stress being applied to the medial collateral ligament (MCL), often resulting in a tear of that structure.
2. ***Compression***—Compressive stress is the axial stress that occurs when a load pushes or squashes molecules together. Take the example of the lateral blow to the knee. Tension is applied to the medial side, but a compressive stress may be experienced in the lateral tibiofemoral compartment that may result in a bone bruise or osteochondral injury.
3. ***Shear***—While tension and compression act in the axial plane, shear stress occurs as a result of forces acting perpendicular to this plane. Again, with the example of the above knee injury, shear stress observed in the lateral compartment may result in abnormal lateral meniscal loading and can result in a meniscal tear.

The majority of sports injuries do not occur as a result of simple uniaxial forces applied to the body. There are often combined loads such as the simultaneous compression and tension that is applied to a long bone when landing a ski jump. In the event of a ski catching an edge, the leg may have a torsional load applied to it; that is a load that acts about the long axis of the bone in rotation, due to the large lever arm and subsequent rotational moment applied by the ski. This may result in a spiral fracture of the tibia or femur [3].

When external forces are applied to a body, deformations occur. ***Strain*** is the quantification of the deformation of a material. When tensile or compressive forces are applied to an object, ***linear strain*** occurs due to the change in the object's length. This can be described in terms of the percentage of length change in relation to its original length [2].

Staying with the example of the MCL injury, a tensile force is applied to the medial aspect of the knee, secondary to the direct lateral blow. The tensile force exerts a linear stress to the MCL which in turn will cause a change in length of the tissue—also known as strain. The close relationship between stress and strain explains the behavior of a material or, in this instance, the MCL, under load.

The relationship of stress and strain can be illustrated via the ***stress-strain curve*** (Fig. 3.1). In the initial linear portion, there is a direct correlation between stress and strain. This is known as ***elastic behavior***, where the material returns to its original dimensions following removal of the applied load. The steeper the line, the stiffer the material, with the slope of the stress-strain curve representing the ***elastic (Young's) modulus*** of the material [2].

With continued applied load, the relationship will eventually not be directly proportional or linear; at this point it reaches the material ***yield***

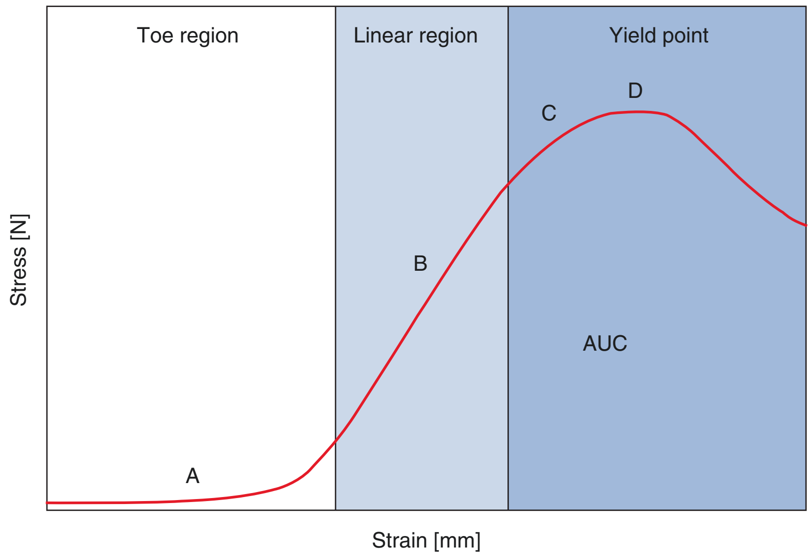

Fig. 3.1 The sinusoidal curve of the biomechanical behavior of the ligament submitted to the uniaxial tensile load. In the segment A of the diagram (toe region), lower force/stress followed by higher strain is observed, reflecting the crimp and nonuniform pattern of the fibers as they elongate. In B (linear region), a progressive stretching of fibers characterized by linear and elastic behavior is verified. The point C is the transition between the elastic limit and plastic region (yield point) and the maximum strength of the material, while the tissue damage (irreversible or permanent deformation) is present in D. The involved energy of rupture in the process is calculated by the area under the curve (AUC)

point and enters the ***plastic region***. In this region, the material no longer returns to its original dimensions and displays ***plastic deformation***. Once the material starts to continue to display increased strain with no further stress applied, it reaches its ***ultimate strength***, with the ***failure strength*** encountered on discontinuity or breakage of the material. For the MCL, a grade II MCL strain will result in a degree of plastic deformation and discontinuity of some of its fibers, with some remaining intact. Therefore, a complete MCL injury may not be observed [4, 5].

The degree of injury that is observed with an applied load is related to the ***viscoelastic behavior*** of musculoskeletal tissues. These material properties, and the way forces are applied to the material, will determine the nature and the severity of the injury [4].

Viscoelasticity: Musculoskeletal tissues, such as the bone, muscle, tendon, and ligament, are known as viscoelastic materials, and their biomechanical behavior is time-dependent, which results from a complex interaction between molecules of proteoglycans, water, collagen, and other components [1, 6]. Abrahams states that viscoelastic tissues work as a combined elastic solid and viscous fluid [7]. The elastic component presents a proportional deformation to the applied force, while the response of the viscous component is time-dependent. In certain conditions, one of these mechanical responses becomes more prevalent than the other, depending on the physical demand. Otherwise, their mechanical behavior has geometrical and structure specificity, as their anatomical site qualifies them mechanically.

Different viscoelastic materials behave differently depending on how quickly load is applied to them. Cortical bone, for example, is stronger and stiffer if a load is applied quickly, whereas it is weaker if applied slowly. This phenomenon of ***strain rate*** can help explain why avulsion fractures occur (Fig. 3.2). In the scenario of an eversion ankle injury, load applied quickly across the joint will more likely result in a deltoid ligament tear, whereas, if it is applied slowly, an avulsion of the tip of the medial malleolus may occur.

Fig. 3.2 PCL tibial avulsion fracture of the left knee in a 22-year-old BMX athlete

Understanding these principles of how load is applied to the body during sport may help understand the mechanism of injury, the injury pattern, and the methods to prevent injury. We will now look at specific tissues and how they have adapted to respond to these external loads.

3.3 Biomechanical Principals of Specific MSK Tissues

Tendons and ligaments: Tendons and ligaments are made up of bands of collagen fibers organized in parallel along their long axis. Both are extremely specialized structures, specifically adapted to bear tensile forces across joints. However, the variations of the ultrastructure pattern of ligament fibers (wavy pattern, called crimping) and their orientation allow them to resist higher levels of strain compared to tendons [4].

When applying tension to the ligament, elongation takes place, and more ligament fibers are recruited. The fibers become gradually uncrimped and oriented in a parallel fashion toward the applied force [1, 8]. As mechanical stress continues, the ligament gradually stiffens until it reaches its ultimate strength and fails. Figure 3.1 illustrates the nonlinear mechanical response (sinusoidal curve), which is a characteristic of the ligament when stressed at different levels of strain.

Bone: Bones are harder and stronger than cartilage, because their structure combines hard mineral (hydroxyapatite carbonate) and flexible collagen, without being brittle. Bones are ductile structures, which are able to adapt their mechanical response according to the direction of the applied force (***anisotropy***). A remarkable example is that bones can resist 30% more load applied through their longitudinal axis compared to their transversal axis (15 MPa and 12 MPa, respectively). Moreover, they have the ability of remodeling and will adapt their structural density to the mechanical environment and are highly specialized in supporting load, mainly in compression. In the elastic phase, the bone can deform up to 0.75%, and, with the deformation of 2–4%, a fracture often occurs. During the plastic deformation phase, the bone can absorb six times more energy before a fracture during the elastic period [9, 10].

During the human biological development, the biomechanical properties of the bone differ according to age. Compared to the immature bone of children, the adult bone is stiffer (more mineralized) and more brittle, while in children it is weaker (less mineralized) and ductile, which is a point to consider when developing a regimen of sports training for children [10].

In sports, athletes perform high-demand physical activities at different levels of speed in short periods, exposing them to direct and indirect loads. Take the example again of the running back colliding with the linebacker. Both players have adapted their bodies to be able to withstand with levels of external load. In some circumstances, the energy of the associated trauma overpowers the bones' ability to withstand the applied load, depending on its direction of application, and thus a fracture may occur.

Frequently, low-energy traumas are linear and do not promote large displacements, while higher-energy traumas will promote significant fracture comminution and dislocation and, subsequently, a substantial associated soft tissue damage. Therefore, the magnitude, duration, direction, and rate of the applying load play a critical role in defining the fracture pattern [9, 10].

A fracture occurs in the weakest plane of the bone, where there is a maximum of shear and tensile stress. According to the loading mode, different configurations of fractures could be produced; for example, a torsional load causes a spiral fracture, while compressive load leads to oblique fractures and combinations of bending and compressive forces result in transverse fractures or a so-called "butterfly" fragment [8] (Fig. 3.3).

Stress fractures: In sport, stress fractures can result from abnormal loads to the bone and can also occur due to muscle fatigue [11]. They frequently occur in individuals who are not adequately prepared for vigorous physical exercises and also in high-performance athletes of sports in which repetitive impact actions are performed, such as volleyball, athletics, and distance running. Dancers may also be subject to this type of injury. From a biomechanical point of view, it can be concluded that in these clinical situations, it is observed that constant load or strain, close to the physiological limit of tissue, could cause plastic deformation and consequently fracture. Besides that, osteoporosis (elderly athletes), preexisting metabolic bone disease (hyperparathyroidism, adrenal disorders), bone neoplasms, drug and alcohol use, vitamin D deficiency, and steroids could predispose to stress fracture (Fig. 3.4).

Muscle: Muscle injuries represent one of the most common clinical problems that cause suspension of sports activity for athletes. Skeletal muscle is the largest tissue in the body, accounting for 40–45% of body weight. Indirect (intrinsic) muscle injuries, also called stretching, and direct injury (extrinsic) are quite common in sports and recreational activities and are produced by direct and indirect trauma. Delayed-onset muscle soreness (DOMS) pain is another muscle problem that occurs with extreme exertion.

It is the mechanism of traumatic injury of the muscle where the ***direct force*** can produce

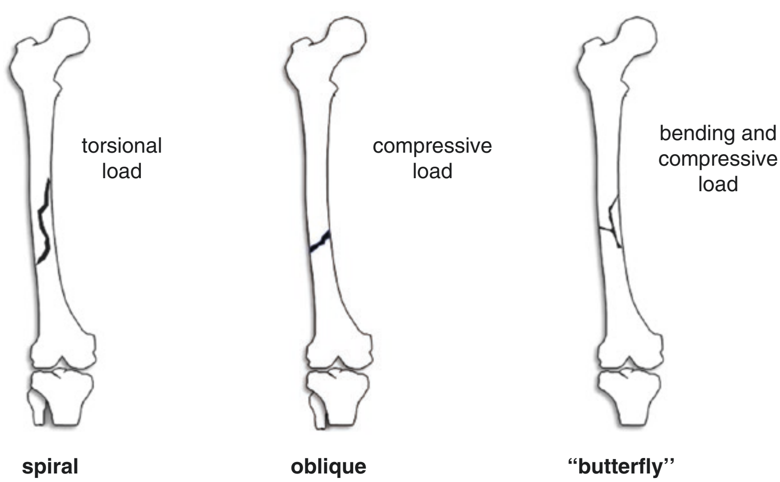

Fig. 3.3 Examples of fracture patterns according to the applied load

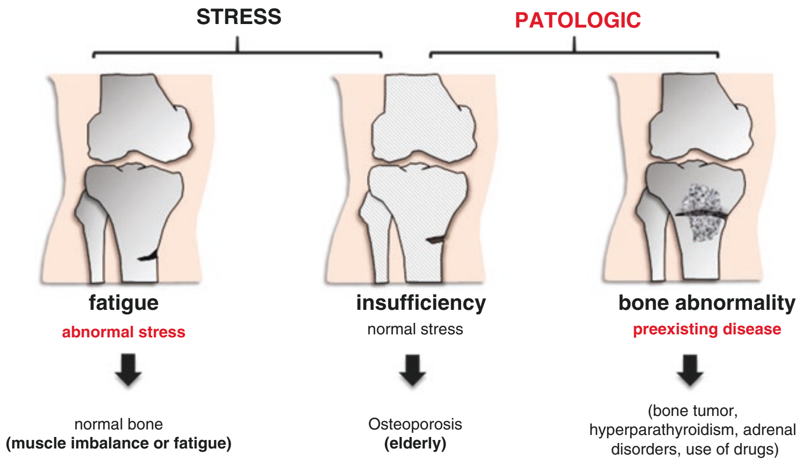

Fig. 3.4 Mechanism of stress fracture according to the quality of bone and mechanical stress (Source: adapted from Greenspan A, editor. Orthopedic Imaging: A Practical Approach. 4th ed. Philadelphia (PA): Lippincott Williams & Wilkins, c2004. Chapter 4, Radiologic Evaluation of Trauma, Figure 4.27, p. 57)

superficial injury, called muscular contusion (bruise), or deeply, characterizing more extensive muscular injury. Bleeding within the muscle can create increased pressure, cell necrosis, and inflammation. Moreover, heterotopic ossification may occur, which can be a major issue for athlete, eventually also leading to disability to continue sporting activity.

Muscle **activation** produces force within the muscle. During a concentric contraction, the resistance load is lower than the force generated by the muscle, and hence it shortens.

On the other hand, if the resistive force is higher than the force generated by the muscle, the muscle is elongated, and an eccentric contraction takes place. This type of muscle contraction is particularly vital in absorbing energy and protecting the joints, as in the case of the landing of the heel, where the quadriceps muscle contracts, protecting the knee. Loss of eccentric quadriceps strength in the postoperative phase of anterior cruciate ligament (ACL) reconstruction can result in a stiff knee landing with an inability to absorb load, predisposing athletes to a higher risk of ACL reinjury. ***Indirect muscle injury*** results from eccentric muscle contraction, which presents a clinical situation where the physiological limit of muscle elongation is exceeded and muscle fiber rupture occurs. These mechanisms usually are loads or velocity dependent [12].

3.4 Sports-Specific Injury Mechanisms

Mechanical factors that cause a musculoskeletal injury can be divided into both extrinsic (from factors outside the body) and intrinsic (from factors within the body) [13]. The primary extrinsic factor is physical contacts either between athletes or with other objects including the ground, shoes, or orthotic equipment. These additional extrinsic factors can aggravate mechanical stresses on musculoskeletal structures. Intrinsic factors include muscle strength and imbalance, body size, flexibility, anatomic alignment, and morphology.

In order to estimate the relative risk of an injury to the athlete, the frequency and magnitude of the physical contacts in each sport should be recognized. Categorization of sports established by the American Academy of Pediatrics Council on Sports Medicine and Fitness (Table 3.1) is most commonly used and quite useful for sports physicians [14]. Contact sports (e.g., soccer and basketball) include those where athletes routinely make contact with each other or with static objects, and some of them are classified as collision sports where the players' hits are made with great force. Limited-contact sports (e.g., baseball and handball) involve infrequent contact between athletes or between athletes and static objects. Non-contact sports (e.g., golf and swimming) are those where physical contact is

Table 3.1 Sports classification based on contact (Proposed by the American Academy of Pediatrics Council on Sports Medicine and Fitness)

Contact	Limited contact	Non-contact
Basketball	Adventure racing	Badminton
Cheerleading	Baseball	Bodybuilding
Diving	Bicycling	Bowling
Extreme sports	Canoeing or kayaking (white water)	Canoeing or kayaking (flat water)
Field hockey	Fencing	Crew or rowing
Gymnastics	Field events	Curling
Martial arts—sparring	High jump	Dance
Judo	Pole vault	Field events
Jujitsu	Floor hockey	Discus
Karate	Flag or touch football	Javelin
Kung-Fu	Handball	Slot-put
Taekwondo	Horseback riding	Golf
Rodeo	Martial arts—forms	Orienteering
Skiing, downhill	Racquetball	Power lifting
Ski jumping	Skating	Race walking
Snowboarding	Ice	Riflery
Soccer	In-line	Rope jumping
Team handball	Roller	Running
Ultimate Frisbee	Skiing	Sailing
Water polo	Cross-country	Scuba diving
Wrestling	Water	Swimming
Collision sports	Skateboarding	Table tennis
American football	Softball	Tennis
Boxing	Squash	Track
Ice hockey	Volleyball	
Lacrosse	Weight lifting	
Roller derby	Windsurfing or surfing	
Rugby football		

rare and mostly unexpected. Typical injuries and their mechanisms in each category of sports are illustrated in this section.

Collision sports: Physical contact with great force, or simply collision, is the main characteristic of collision sports and the primary reason for a high prevalence of musculoskeletal injuries. In collisions, energy is transferred from one body to another. In blocking and tackling, for example, transfer of energy between bodies can result in injury when the energy transferred exceeds the tolerance of the involved tissues (e.g., bones, tendons, ligaments). It is reported that American football has the highest injury rates at both the high school [15] and collegiate [16] levels. Thus, collision sports have undoubtedly the highest risk of injuries among all categories.

Acute traumatic fracture by applying a single high-magnitude load to the bone is one of the typical injuries. Such a fracture happens when the force exceeds over the bone's ability to resist it. Traumatic fractures are often seen in player-to-player contact, and the highest rate of fractures was reported as being more than 10% in American football according to the epidemiological study of high school athletes [17].

Contusion is also common in collision and contact sports, since it occurs when a direct blow or repeated blows from other players or a blunt object strike part of the body, crushing underlying muscle fibers and connective tissue. It consists of 20-30% of all the injuries in rugby players [18], whereas basketball, a contact sport, has fewer contusions, e.g., 15.3% on the professional league level [19]. However, most of these injuries are minor and heal quickly, without taking the athlete away from competition. But, once deep tissue is damaged, it may keep the athlete out of sports for months.

Contact sports: Musculoskeletal injuries in contact sports commonly occur by direct contact with another player. In basketball, player-to-player contact accounted for 79.8% of contact injuries and 34.9% of all injuries [20]. The most common injury is lateral ankle sprain, accounting for 13.2% of all injuries on the professional league level [19]. Lateral ankle sprains occur by landing on another player's foot and/or out of balance due to contact with other players, while most of the player's attention is paid to the ball and the rim above his/her head. Forceful ankle plantar flexion and inversion may damage the lateral ligaments of the ankle. Considering that the greatest number of injuries occurred within the three-point line [20], the amount of playing time spent is the key (greater exposure), and the increased player-to-player contact due to higher player concentration could be a major reason for high prevalence of lateral ankle sprains in basketball. Much attention has focused on prevention of ankle inversion injuries in basketball. The design of the shoes has been adapted subsequently to protect the ankle, and many players also tape their ankles or additionally wear braces. However, the persisting high frequency of ankle injuries suggests that more clinical and biomechanical research is necessary to improve protective shoe and ankle equipment.

Limited contact sports: Although the frequency and magnitude of contacts are fewer and smaller in limited contact sports compared to collision or contact sports, injuries in limited contact sports still mainly result from direct physical contact.

Fractures of the hand are quite characteristic of baseball and softball and are frequent causes for surgery [17] and subsequent disqualification from the game [21]. Rare but quite strong force is applied when the high-speed ball hits the player's hand at the time of batting or catching. Hand fractures can significantly limit sport participation [22], since most of the players have to utilize their hands independent of the sport practiced.

Non-contact sports: Musculoskeletal injuries in non-contact sports are mostly caused by repetitive or extreme force that is generated by athletes' own exertion.

Muscle strain is a quite common injury which refers to damage of a musculotendinous unit (or muscle-tendon complex). Acute muscular strain can result from overstretching an inactive muscle or dynamically overloading an active muscle either in concentric (active shortening) or eccentric (active lengthening) action. The leg or groin muscles, such as quadriceps and hamstring muscles, are most frequently affected. Hamstring muscle strain is more often seen in track athletes than in any other sports according to the report of NCAA athletes [23].

Fractures typically occur by applying a single great external force directly to the bone. But bones may also fracture in response to repeated low-magnitude loads, which results in what has been described as a stress fracture previously [11]. The magnitude of forces is less than the maximum tolerated by the bone, but applied repetitively, causing a disruption in the bone. The incidence of stress fractures in the general athletic population is approximately 1%; however, the incidence may be as high as 15% in certain populations at risk, such as runners [24]. Also, track and field athletes have a higher incidence of stress fractures than participants of contact sports, such as football, soccer, or basketball [25]. Furthermore, stress fractures are generally more difficult to be diagnosed and treated than traumatic fractures.

The categorization of sports indicates the comparative likelihood that participation in different sports will result in acute traumatic injuries from blows to the body. On the other hand, overuse injuries are also typical in athletes and mostly not related to contact or collision but to repetitive microtraumas. Furthermore, overuse injuries generally are not acute. Therefore, the applied categorization might be insufficient to adequately attribute relative risks of such overuse injuries. Further assessment of sports participation in terms of duration and intensity should be considered here.

Additionally, the prevalence of the injury can be differing among field positions, especially in team sports. For example, shoulder injury rates are much higher in flanker and five-eighths than in halfbacks in rugby [26]. Besides the field position, physicians might also consider the level of competition, the maturity of the competitors, the relative physical size, and the availability of effective protective equipment for further biomechanical assessment of musculoskeletal injury.

In summary, musculoskeletal injuries occur as a result of forces that are applied to the body. Understanding these forces and how they interact with individual MSK tissues is extremely important when treating sports injuries. Injury mechanisms can be specific to individual sports, and the sports categorization based on the contact level is useful to estimate the relative risk of musculoskeletal injuries.

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