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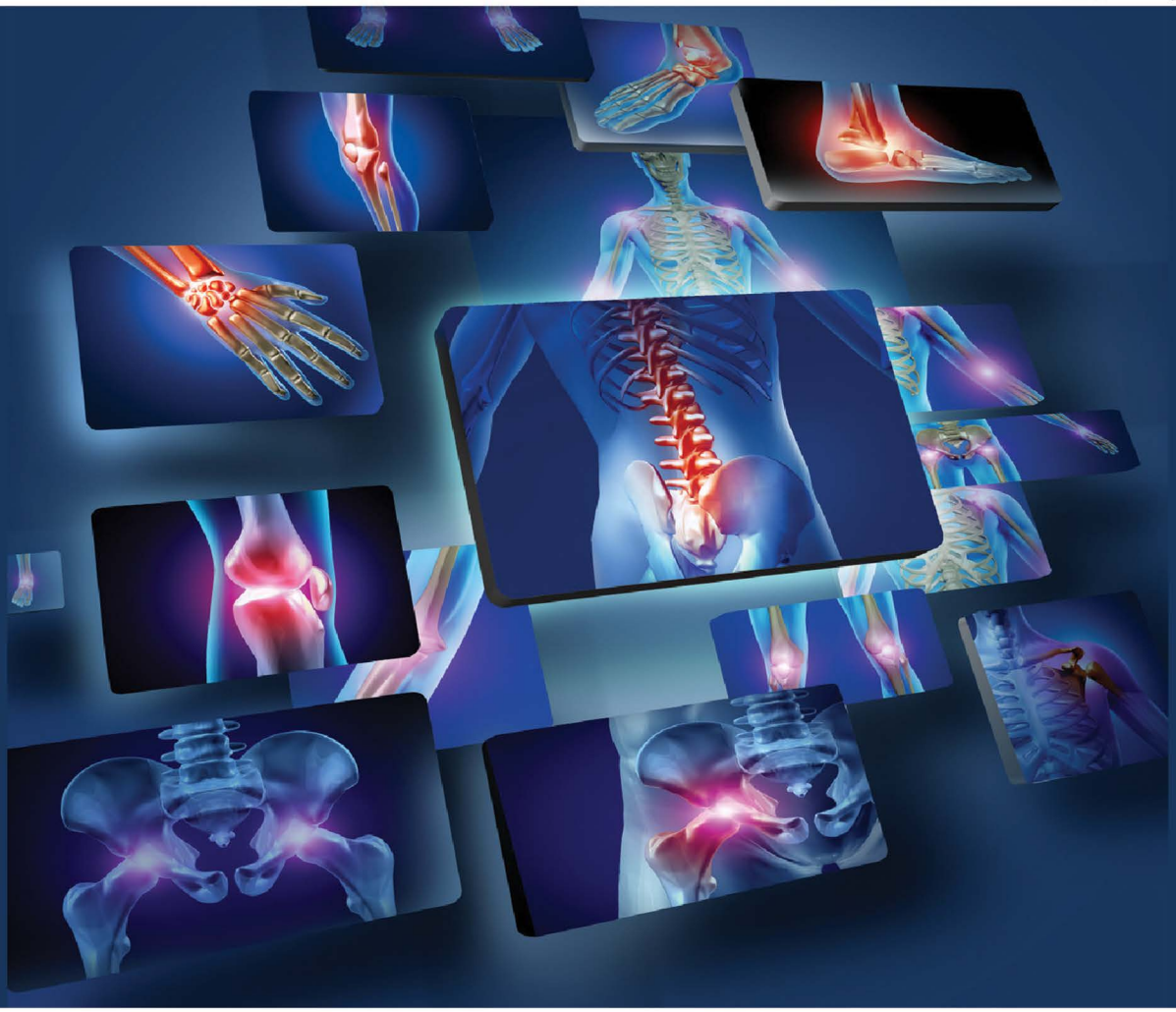
Textbook of Orthopedic Rheumatology



Manish Khanna

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2 Biomechanics of Joints

Subir Kumar Mukherjee, Alok Chandra Agrawal, Mukund Madhav Ojha

INTRODUCTION

"Nothing happens until something moves."

—Albert Einstein

If we look into our surroundings, we will be amazed at the biomechanics involved in the intricate and skilled movements of dancers, musicians, toddlers, and even animals. Needless to say, scholars from aeons ago have devoted themselves in studying movements in animals and humans. Human body may be viewed as a machine comprising different parts that allow movements which occur at different joints formed by the specific parts of body's musculoskeletal system. The very essence of this chapter is to develop a lucid and coherent understanding of clinical useful biomechanical concepts used for elucidating changes in joint functions.

Certain terminologies pertinent to this chapter:

- *Mechanics*—study of forces and their effects.
- *Kinematics*—branch of mechanics that deals with the geometry of the motion of objects, including displacement, velocity, and acceleration, without taking into account the forces that produce the motion.
- *Kinetics*—study of the relationships between the force system acting on a body and changes produced in body motion.
- *Force*—action exerted on a body that causes it to deform or to move.
- *Biomechanics*—study of continuum mechanics (i.e., the study of loads, motion, stress, and strain of solids and fluids) of biological systems and the mechanical effects on the body's movement, size, shape, and structure. It ascends from molecular level to systemic level.
- *Molecular biomechanics*—study of how mechanical forces and deformation affect the conformation, binding/reaction, function, and transport of biomolecules like DNA, RNA, and proteins.
- *Cellular biomechanics*—study of how cells detect mechanical forces or deformations, and transduces them into biological responses, especially for the study of how mechanical forces change cell growth, differentiation, movement, signal transduction, protein secretion and transport, and gene expression and regulation.
- *Tissue biomechanics*—study related to growth and remodeling of tissues as a response to applied mechanical stimuli.

For instance, Julius Wolff in 19th century postulated a law on bone remodeling, famously known as Wolff's law which states that internal architecture of the trabecular and cortical bone in a healthy person or animal will adapt to the loads placed on the bone and it will remodel itself over time to become stronger to resist that type of loading. The reverse also holds true.

- *Systemic biomechanics*—study concerned with highly coordinated mechanical interaction between bones, muscles, ligaments, and joints within musculoskeletal system under control of nervous system.

Why to give emphasis on understanding biomechanics?

There has been constant quest in discovering principles and developing concepts that govern movements. It can be applied for:

- *Performance enhancement*: Biomechanics give a qualitative analysis of the situation thereby aiding sports professionals to adapt techniques needed for effective movements.
- *Designation of sports equipment*: It also helps in modifying and designing equipment keeping in mind the weight distribution, range and time of motion, and shortening or lengthening of equipment.
- Advances in exercise and conditioning programs.

LEVERS

A lever is a rigid bar (bone) that turns about an axis of rotation or fulcrum (joint) when a force (from muscle contraction) is applied against a resistance (weight, gravity, etc.). Levers are used to alter the resulting direction of the applied force. Lever can be categorized on the basis of relationship of fulcrum/arm (A) to force (F) and resistance (R) **(Table 1 and Fig. 1)**.

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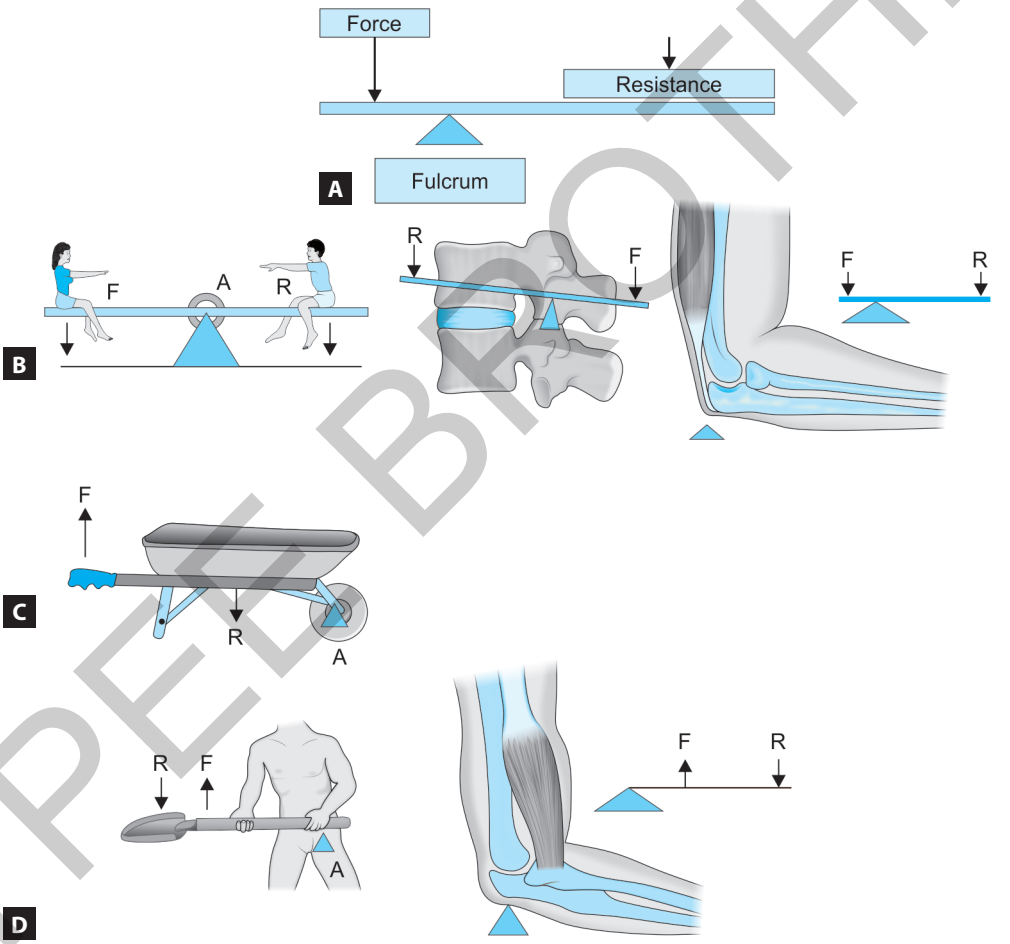
TABLE 1: Classes of lever.

Class I lever	*Class II lever*	*Class III lever (most common)*
F-A-R	A-R-F	A-F-R
Resistance and force are always opposite	Resistance and force are in same direction	Resistance and force are in same direction
1. Balanced movements—axis near middle, e.g., erector spinae neck extension 2. Speed and ROM—axis near force, e.g., extension at elbow through triceps contraction 3. Force—axis near resistance	Force—axis near resistance, e.g., plantar flexion through gastrocnemius and soleus contraction	Speed and ROM—axis near force, e.g., flexion of elbow joint through biceps contraction

(A: axis; F: force; R: resistance; ROM: range of motion)



Figs. 1A to D: (A) Lever system showing components; (B) First-class lever system; (C) Second-class lever system; (D) Third-class lever system. [A: axis (fulcrum); F: force; R: resistance]
Source: Chapter 2: Joint anatomy and basic biomechanics. In: Bergmann TF, Peterson DH (Eds). Chiropractic Technique: Principles and Procedures, 3rd edition. Mosby; 2010.

BODY PLANES AND AXES OF MOVEMENT

For explaining structural position and movement directions, there should be allocation of body planes with reference to anatomical position. An axis is a line around which movement occurs. Three dimensional coordinate system with X, Y, and Z axes are used in locating the extent of types of movements permissible at each joint like **(Table 2 and Fig. 2)**:

- Rotational—all movements that occur about an axis
- Translational—linear movements along an axis and through a plane
- Curvilinear—translational movements along with rotational movements.

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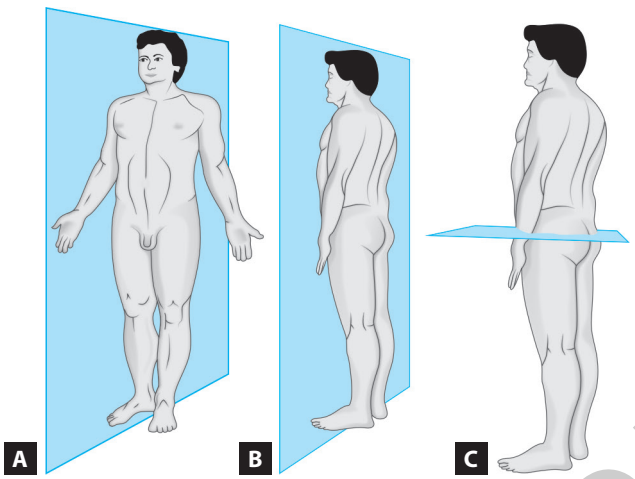
TABLE 2: Body planes with axis and joint movement.

Plane of movement		*Axis*	*Joint movement*
Sagittal (extends from anterior to posterior)	Vertical	X (junction of coronal and transverse)	Flexion and extension; lateral to medial and medial to lateral slide*
Coronal (extends from side to side)	Vertical	Z (junction of sagittal and transverse)	Abduction and adduction; anterior to posterior, and posterior to anterior glide*
Transverse (divides into upper and lower)	Horizontal	Y (junction of coronal and sagittal)	Medial and lateral rotation (axial rotation) inferior to superior, and superior to inferior glide* (compression, distraction)

*(slide and glide are used to refer translational movements between joint surfaces.)



Figs. 2A to C: (A) Midsagittal plane; (B) Coronal plane; (C) Transverse plane.
Source: Chapter 2: Joint anatomy and basic biomechanics. In: Bergmann TF, Peterson DH (Eds). Chiropractic Technique: Principles and Procedures, 3rd edition. Mosby; 2010.

JOINT MOTION AND TYPES

Every joint is blessed to exhibit 6° of freedom, three translational and three rotational. The extent of each motion is based on the anatomy of the joint and the plane of the joint surface particularly to spinal joints **(Flowchart 1)**.

SYNOVIAL JOINTS

Synovial joints are the most common, highly evolved, and freely movable joints. These are comprised of bony elements, articular cartilage, fibrocartilage, synovial membrane, fibroligamentous joint capsule, and articular joint receptors.

Bony Elements

It is a type of connective tissue with inorganic constituents like salts. Cortical bone is hard outer shell which surrounds cancellous bone thereby providing structural support while cancellous bone is inner part containing marrow and blood vessels for nutrition and also contains trabeculations. It plays crucial role in hematopoiesis. Bone is often considered as storehouse of calcium and phosphorus. It has self-repairing quality with its own tissue. It also has best ability for remodeling, repair, and regeneration.

Articular Cartilage

Speciated, avascular hyaline cartilage covering articulating surfaces of synovial joints thereby relaying loads and minimizing friction. Through zone of calcification, it is adhered to subchondral bone. It has four characteristic histological areas given in **Table 3**.

Articular cartilage derives its nutrition from highly vascularized synovium and intermittent compression and distraction needed for adequate exchange of nutritions and waste products. Possesses limited capacity for cartilage repair hence degeneration of articular cartilage depends on the size and depth of lesion, integrity of surrounding articular surface, age and weight of patient, associated meniscal and ligamentous lesions, and other biomechanical factors.

Fibrocartilage

Mostly found in intervertebral discs, pubis symphysis, etc. It mainly applies "load-unload mechanism" for nutrition and eradication of metabolic wastes. Owing to its higher fiber content, it has pivotal role in bolstering and stabilizing joints with subsequent driving off the compressive force.

Synovial Fluid

An ultrafiltrate derived from blood with supplements from synovium, meant for lubrication, protection, and nutrition of articular cartilage. Earlier, hyaluronic acid (secreted by type B cells) was thought of imparting the viscosity to synovial fluid but now it has been investigated that a glycoprotein named "lubricin" secreted by surface chondrocytes and synovial cells possess the same quality due to its surface active phospholipids.

Joint Lubrication Models

Albeit no model is superior to one other, amalgamation of elastohydrodynamic and boundary lubrication model serves a satisfactory explanation to human synovial joint **(Table 4)**.

ARTICULAR NEUROLOGY

Neural innervation of synovial joints is by three or four neuroreceptors, briefly described in **Table 5**.

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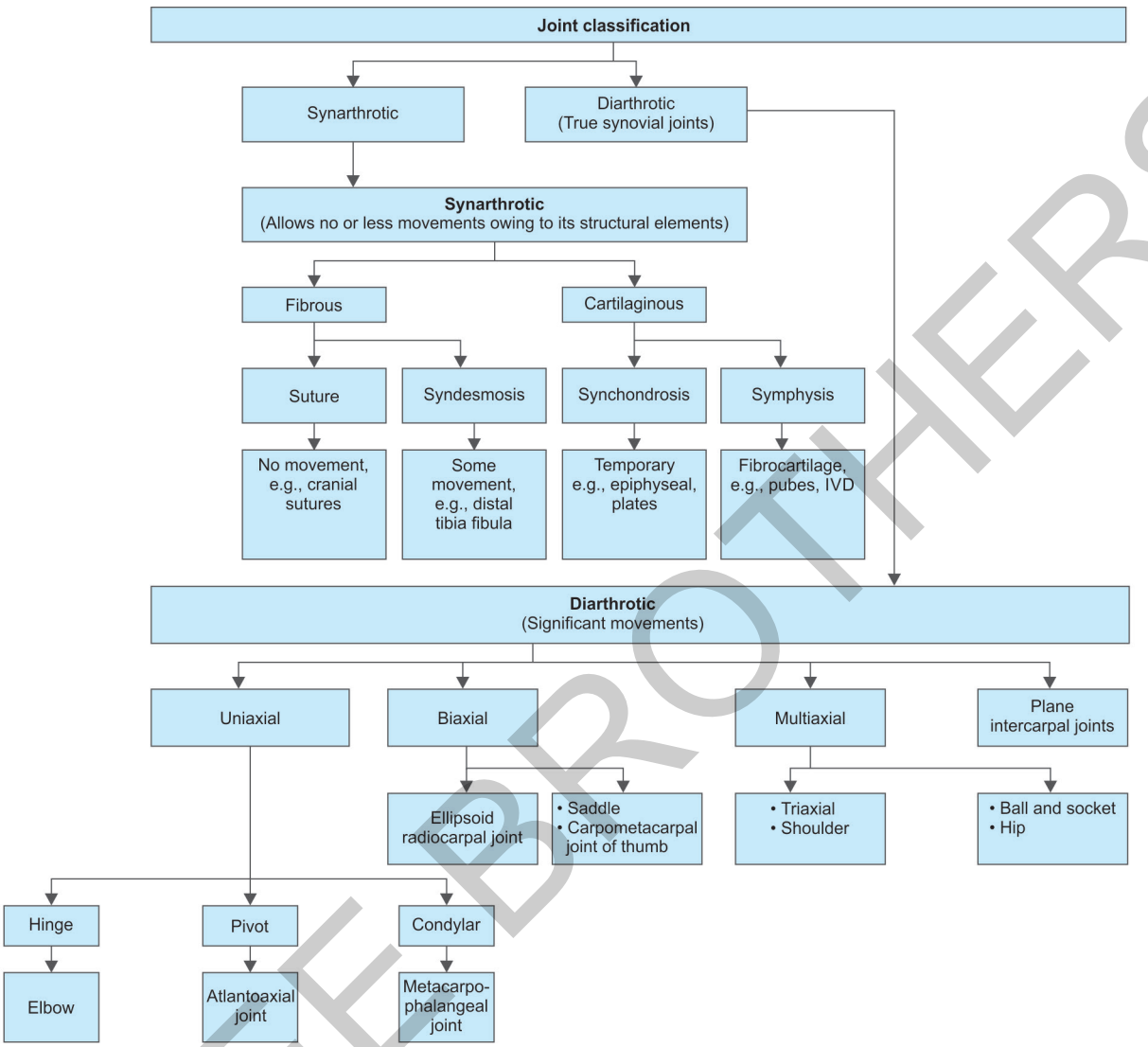
Flowchart 1: Classification of joint.



(IVD: intervertebral disc)

TABLE 3: Zones of articular cartilage.

Gliding zone	Outermost zone with outer superficial layer of random collagen arrangement and inner tangential layer of dense and compact collagen orientation, collateral to joint surface in order to shield deeper elastic cartilage
Transitional zone	Orientational change of fibers from parallel to perpendicular direction
Radial zone	
Zone of calcified cartilage	

TABLE 4: Joint lubrication models.

Hydrodynamic model	Synovial fluid gaps the left out spaces of incongruent joint surfaces and maintains fluid film during movements Advantage—works well with quick movement Disadvantage—inadequate lubrication for slow movements and movements under increased loads
Elastohydrodynamic model	Modified form of previous model. Viscoelastic qualities of articular cartilage minimizes compression stress to lubrication fluid Advantage—explains movements under loading forces Disadvantage—fails to justify lubrication at motion initiation or period of zero velocity during reciprocating movements
Boundary lubrication model	Adsorption of lubricant on joint surface minimizes surface roughness by gap filling and surface coating Advantage—can justify initial movement and zero velocity movements

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TABLE 5: Neural innervation of synovial joints.

Receptors	*Nature*	*Location*	*Function*
Type I (low threshold)	Mechanoreceptor	Outer layer of joint capsule	Posture and motion perception
Type II (low threshold)	Mechanoreceptor	Deepest layers of joint capsule	Movement monitoring for reflex actions (completely shut down in immobilized joints)
Type III (slow adapters)	Mechanoreceptor	Intrinsic and extrinsic ligaments of peripheral joints	Monitors motion direction Braking mechanism against over displacing joint movements
Type IV (very high threshold)	Nociceptor	Fibrous portions of joint capsule, ligaments and synovial folds. (Absent in articular cartilage, synovial linings)	Pain perception (inactive in physiologic joint)

JOINT FUNCTION

The physiologic movements at each joint occurring due to muscular contraction or acting gravity is known as "*osteokinematic movement*." It speaks about the relativity of each joint with each other.

A concatenation of segmental linkage, i.e., connected shoulder girdle, arm, forearm, wrist and hand of upper extremity, is often known as kinematic chain, which can be either closed or open. Fixed distal segment to immovable object while keeping proximal segment free is called closed chain while in open chain, distal segment is free and not connected with fixed object.

Movements occurring at the articulated joint surfaces are known as *arthrokinematic movement*. While evaluating joint motion, it is thus imperative to relate osteokinematic movement to arthrokinematic movement. Various permutations and combinations like roll, spin, and slide occur during relative movements of joint surfaces.

- Roll occurs when points on one bone surface coincides with points on other bone at same interval.
- Spin—rotational movement around mechanical axis. Possible in hip, shoulder, and proximal radius.
- Slide—when single point on moving joint coincides with many points on opposing joint surface.

For normal joint function, joint motion must possess five traits which are joint play, active range of motion, passive range of motion, end feel or play, and paraphysiologic movement. Joint movement beyond the paraphysiologic barrier departs from confinement of anatomic integrity subsequently making an entrance into pathologic zone.

HUMAN MOTION ANALYSIS

It is defined as the systematic study of human motion by careful vigilance, supported by instrumentation for measuring somatic movements, body mechanics, and muscle activity. It is often used to gather quantitative data about the mechanics of the musculoskeletal system during motor performance.

A special branch related to human walking is "*gait analyses.*" Eadweard Muybridge is regarded as the "Father of Modern Gait Analysis" attributed to his pioneer work in gait. Carl Pulfrich is widely known as the "Father of Stereophotogrammetry", a technique used to measure 3D landmark coordinates. The quantifiable values to assess human motion analysis are musculoskeletal movements defined by skin markers and measured by motion capture systems and external forces applied by force plates. The 3D trajectories of skin markers derived from stereophotogrammetry, the GRFs (ground reaction forces) and the center of pressure measured via force plates, intersegmental forces, and internal moments at joints of lower limbs are calculated from the solution of equations based on Newton's laws of motion. This process is known as "inverse dynamics analyses."

IMPLEMENTATIONS OF BIOMECHANICS

- Useful diagnostic and investigative tool in research and clinical areas.
- Identification of any deviation from normal movement with simultaneous evaluation of neuromusculoskeletal conditions and treatment planning, e.g., cerebral palsy, osteoarthritis of knee, paraplegia, etc.
- Important role in assistive technology such as prosthetics, orthotics where critical joint motion are precisely evaluated.
- Helps in honing athletic performance, detecting common sports injuries along with posture and movement related problems.

APPLIED BIOMECHANICS

Biomechanics is a continuous evolving branch of science where engineers and doctors work together for the betterment of human disability. Any disarray in the normal kinematics of joints sets off a vicious cycle of disturbed biomechanics which in turn further damages the joint. Principles of biomechanics and human motion analysis are used to study the pathobiomechanics occurring due to various joint pathologies. Purpose of any musculoskeletal surgeries and rehabilitation protocols is to ameliorate the pathobiomechanic processes occurring at joints, bone, or

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muscles and reinstate the normokinematics so as to work in harmony.

BIOMECHANICS OF FRACTURE FIXATION

In this era where conservative treatment of fracture has shifted to operative procedures, newer techniques and implant designs (dynamic compression plate, locking compression plate, and intramedullary nails) for fracture fixation are available. Biomechanics involved in fracture fixation using these implants persuade the fracture healing. Perren described strain to be the limiting factor for the final outcome of fracture healing **(Table 6)**.

Various parameters like fracture morphology (simple or comminuted), soft tissue status, implant used (plate or nail), implant material (titanium or stainless steel), and mode of implant application affect the final outcome of fracture healing.

Working length of an implant bone construct is the distance between the proximal and distal end points where implant is fixed to the bone across the fracture site. Working length is inversely related to fracture fixation stability. Increasing working length results in decreased fracture stability at far cortex to produce enough micromotion ensuring optimum callus production. This principle is used for secondary fracture healing in comminuted fractures.

BIOMECHANICS OF ARTHROPLASTY

Osteoarthritis is one of the most common causes for disability in the world. It is a disease of the whole joint which includes muscles, tendons, ligaments, synovium, and bone. Altered loading mechanisms, increased mechanical forces, and changed biomechanics in weight-bearing joints are imperative factors responsible for initiation and progression of osteoarthritis. It is most common in weight-bearing joints like hips, knees, and ankle but can also occur in any synovial joint of the body. Biomechanically, knee acting as polycentric joint bears higher shear forces in comparison to hip or ankle joint as it involves sliding, rotating, and rolling motions during movements. Any imbalance between repair mechanisms and destructive forces can sabotage the joint homeostasis resulting in osteoarthritis though congregation of structural reaction of joint tissues to mechanical stimuli is the current cognizance of pathogenesis of osteoarthritis. Joints connected serially act as kinematic chain which allows movement with subsequent stability, congruency, and shock absorption. For optimal load reduction and distribution and painless gliding, alignments, adduction movements, and muscle balancing are principle factors and thus unphysiological loading patterns on one joint may impact the near by joints too. The alignment of lower extremity is known as mechanical axis which is defined as a line drawn from the center of the femoral head to the center of the talus which passes close to the center of the tibial head between the eminentia tibiae, approximately one degree in varus thereby physiologically causing unequal weight distribution of 60–70% on medial compartment and 30–40% on lateral compartment, which is a predisposing factor for medially accentuated tibiofemoral osteoarthritis. The deviation of mechanical axis drastically reduces the load bearing area and amplifying the resultant load to the remaining joint surface. By human motion analysis, gait analysis (a noninvasive, indirect, and most common method) uses video cameras and ground reaction force plates summarize pressure and movements transforming information to external moments relative to internal joint loads. In varus arrangement, the adduction moment (AdM) is a varus torque on the knee joint which is determined by the ground reaction force (GRF—force generated by the foot touching the ground) and by the distance of the GRF vector from the center of the knee joint. At early and late stance phase (heel strike to foot flat and toe off), a valgus moment is present together with maximal compressive forces on lateral knee compartment. During midstance phase, a varus moment occurs to the knee in line with maximum compressive forces on medial knee compartment. Anything which decreases AdM at knee tends to relieve symptoms of osteoarthritis like conservative strategies in form of lateral wedge insole, valgus knee braces, gait modification with toe out gait, weight loss, etc. Joint preserving surgeries can restore normal biomechanics with simultaneous reduction in pain and functional improvement. Young and active patients may get maximum benefit from these surgeries which include correction osteotomy either open or closing wedge, orthobiologics and viscosupplementation, autologous chondrocytes implantations (ACL), transplantation of osteochondral allografts, or mosaicoplasty. In advanced cases where articular cartilage is severely destroyed, total joint replacement is the treatment of choice in which soft tissue balancing plays a key role in deformity correction and restoring the normal alignment.

Biomechanical studies are equally important in understanding hip movements and hip joint reaction forces. The biomechanical principle guide engineers in proper designing of components of hip replacement implants. From various studies conducted in vitro and in vivo have helped in executing therapeutic programs to relieve symptoms thereby delaying the disease progression of

TABLE 6: Strain as the limiting factor.

Strain	*Stability at fracture gap*	*Type of fracture healing*
≤2%	Rigid fixation	Primary or direct without callus formation
2–10%	Allows micromotions	Secondary or indirect with callus formation
>10%	Unstable	Leads to nonunion

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hip pathology. The biomechanics and biomaterials are important components attributed to the success of total hip arthroplasty in pain alleviation and functional restoration.

BIOMECHANICS OF SPINE AND PRINCIPLE OF DEFORMITY CORRECTION

Any spinal deformity whether acute or chronic commences with instability in at least one motion segment which can be corrected by various methods with its pros and cons. Forces on spine can be divided into component vectors. Instantaneous axis of rotation (IAR) is an axis around which the bending moment applied to a point in space causes rotation or tendency to rotate. It acts as pivot point around which flexion or extension occurs. Loads applied whether acutely or chronically cause deformation in one of two directions involving one or multiple spinal segments.

Principles Considered during Deformity Correction

The load bearing axis must be considered in both sagittal and coronal planes which is shifted ventrally with flexion and dorsally in extension. It is located in ventral region in normal thoracic spine while in dorsal region in normal cervical and lumbar spine. Sagittal balance of the spine should be kept in mind. Central sacral line (CSL) is perpendicular to a line passing through both iliac crests, ascending rostrally in the line with sacral spinous processes. It is often used to assess balance in coronal plane and scoliosis assessment. The length and location of the stabilizing construct are critical. The apical and neutral vertebrae in coronal and sagittal planes must be evaluated. An implant should not be closed at or near an apical vertebra and hence should be long enough to extend to neutral vertebra. Cervicothoracic and thoracolumbar regions are susceptible to deformity if implants are placed to but not beyond these levels. Disc spaces near the junctional zones are usually not parallel to the ground in the standing position thereby applying angular forces to the spine.

BIOMECHANICS OF SHOULDER AND ITS PATHOLOGY

Shoulder joint is the most complex joint of body where four joints (glenohumeral, sternoclavicular, acromioclavicular, and scapulothoracic) with support from muscles, ligament, and capsule work synchronously in balance to attain multidirectional movements at the cost of stability. Humeral head articular surface is about three times that of glenoid cavity and is made stable by static and dynamic stabilizers around the joints. Rotator cuff (supraspinatus, infraspinatus, teres minor, and subscapularis) is a group of muscles which acts as a key dynamic stabilizer to glenohumeral joint stability at rest and during motion. It presses humeral head to glenoid (concavity-compression principle) and helps in overhead arm elevation. Any disruption in balance leads to mechanical dysfunction in form of rotator cuff impingement or glenohumeral instability. Application of the biomechanical concepts of shoulder is helpful in addressing the rehabilitation protocol to these mechanical dysfunctions after musculoskeletal procedures.

BIOMECHANICS OF REHABILITATION BY ORTHOSES AND PROSTHESIS

Group of splints and appliances, which when applied or fixed to a body part to make it work properly, are called as orthoses, whereas prosthesis acts as proxy to the missing part of the body. Understanding biomechanics of normal and pathological gait helps us to prescribe proper orthoses to the patient. Orthoses are basically designed to overcome the abnormal forces acting on body. Biomechanics helps in development of floor reaction orthoses which are used in cerebral palsy patient with crouch gait (severe knee flexion) to improve gait in midstance by preventing forward tibial progression and therefore helping quadriceps muscle in maintaining knee extension.

SUMMARY

This chapter briefly tells about the very importance of biomechanics of joints. Human beings are constantly insulted by different forces on earth. By studying the interrelationship between these forces and human body movements, we can apply biomechanics principles in uplifting the quality of life. Human movements are highly complicated and are governed by sophisticated interaction between nervous and musculoskeletal system. Any insult to, or injury to any single element of this network will lead to undesired consequences in form of disability. Biomechanics principles and human motion analysis help us to study the disease process and planning the treatment.

KEY POINTS

- Understanding biomechanics is essential for planning of treatment, performance enhancement, and improving quality of life.
- Joints may be synarthrotic or diarthrotic.
- Zones of articular cartilage—gliding, transitional, radial, and calcified.
- Joint lubrication models—hydrodynamic, elastohydrodynamic, and boundary lubrication.
- Perren's strain hypothesis >10% strain leads to nonunion.
- Working length is inversely proportional to stability.

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Textbook of
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Salient features

- Orthopedic rheumatology is a rapidly evolving medicosurgical specialty which is an important subspecialty of orthopedics and at the same time very useful for the orthopedic surgeons busy in the surgical practices. Newer scientific discoveries related to this specialty are largely related to better understanding of immunology, pathogenesis of major ortho-rheumatological disorders which are described as autoimmune disorders
- Caters the academic needs of orthopedic surgeons as well as for those who are interested to learn and practice this superspecialty of the orthopedic rheumatology. The main target audience would be the orthopedic postgraduate (PG) students and those who are doing Fellowship in Orthopedic Rheumatology
- Gives illustrious details of the entire orthopedic rheumatology especially focusing on medical, surgical and rehabilitation part of the subject
- Approx 65–70% of Indian population lives in villages and smaller cities and there the patients have been going to orthopedic surgeons for joint pain, arthritis management, hence there has to be proper training for the diseases (for both medical and surgical reasons) and this textbook would go a long way in catering such needs of orthopedic fraternity and the PG students, not only nationally but also internationally
- Providing latest updates of various surgical procedures in and all around the orthopedic rheumatology thus the textbook would be contributing a lot in the Indian orthopedic academic growth
- Provides a wide spectrum coverage of all the relevant topics of orthopedic rheumatology and a very special emphasis is being given to regenerative medicine in orthopedic rheumatology
- Regenerative science holds great promise to mankind and further have a very strong impact in its clinical implication especially in orthopedic surgery. As orthopedic surgeons continue to face day-to-day challenges regarding the healing of diseased tissues, regenerative sciences aim to develop novel therapies that would replace, repair or promote tissue regeneration
- The potential use of progenitor cells, various growth factors in orthopedic tissue engineering are especially highlighted in the textbook in the Section 9.

Thus, the book would be mainly focusing on the academics and research work in the field of orthopedic rheumatology, regenerative orthopedics/orthobiologics (in the rheumatological part of orthopedic practice).

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