Biomechanics and Sports

Biomechanics and Sports

Skeleton, Joints and Biomechanics of some Sports

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Overview

Introduction

Introduction

- The term biomechanics combines the prefix bio, meaning life with the field of mechanics, which is the study of the actions of forces.
- The international community of scientists adopted the term biomechanics during the early 1970s to describe the science involving the study of the mechanical aspects of living organisms

Introduction

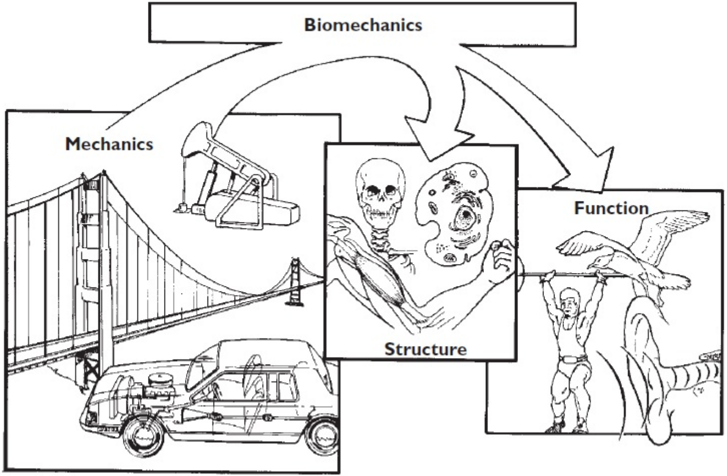
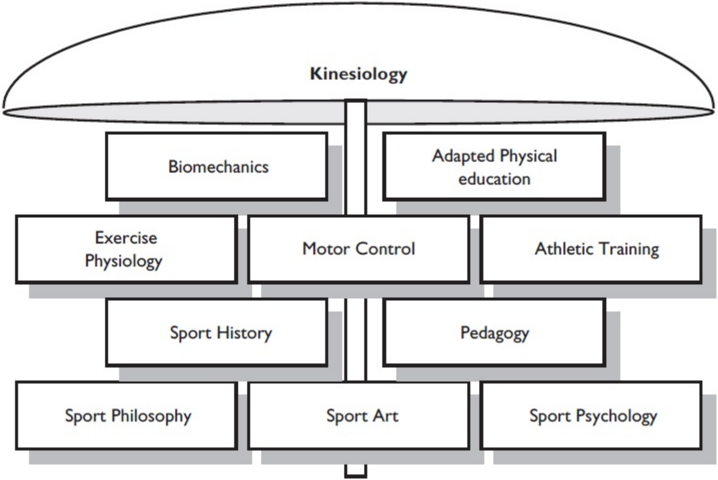
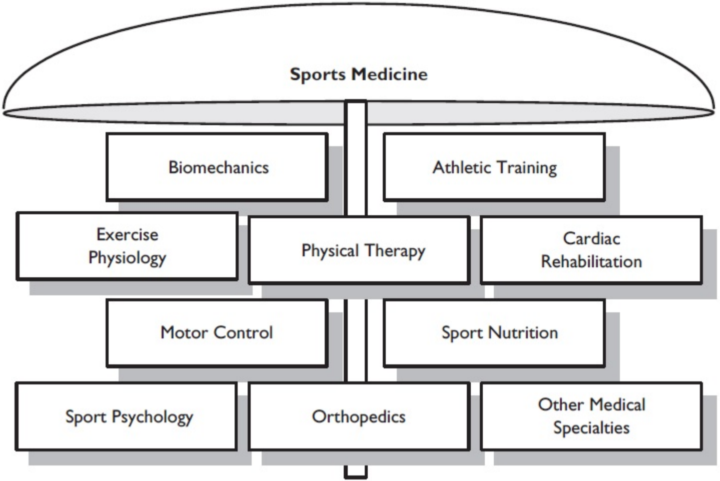


Exhibit 1 : Biomechanics

Introduction



Introduction



Kinematic concepts for analyzing human motion

Kinematic concepts for analyzing human motion

Superior: closer to the head (In zoology, the synonymous term is cranial.)

Inferior: farther away from the head (In zoology, the synonymous term is caudal.)

Anterior: toward the front of the body (In zoology, the synonymous term is ventral.

Posterior: toward the back of the body (In zoology, the synonymous term is dorsal.)

Kinematic concepts for analyzing human motion

Medial: toward the midline of the body

Lateral: away from the midline of the body

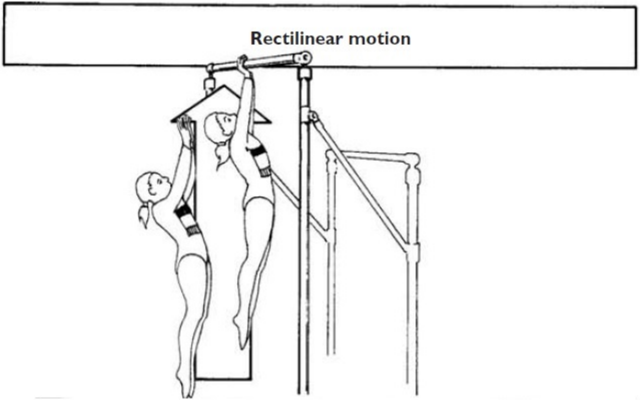
Proximal: closer in proximity to the trunk (For example, the knee is proximal to the ankle.)

Distal: at a distance from the trunk (For example, the wrist is distal to the elbow.)

Superficial: toward the surface of the body

Deep: inside the body and away from the body surface

Kinematic concepts for analyzing human motion



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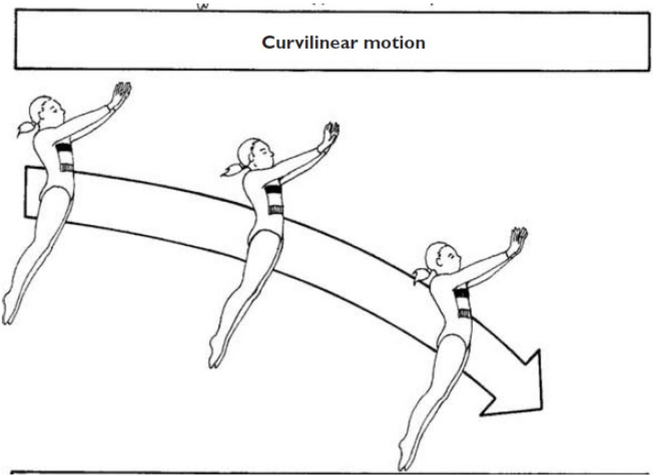

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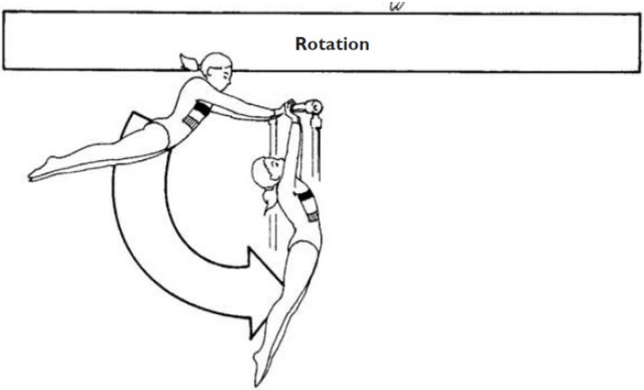

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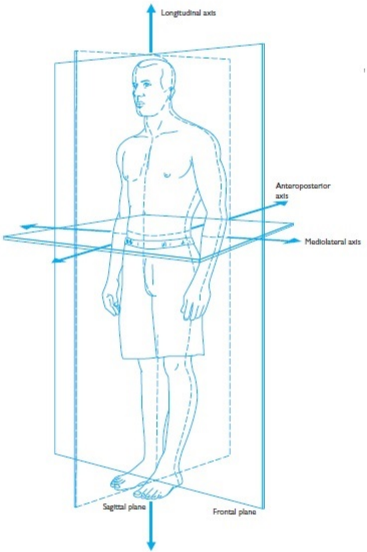

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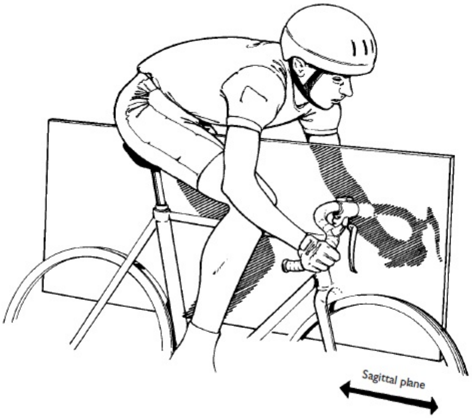

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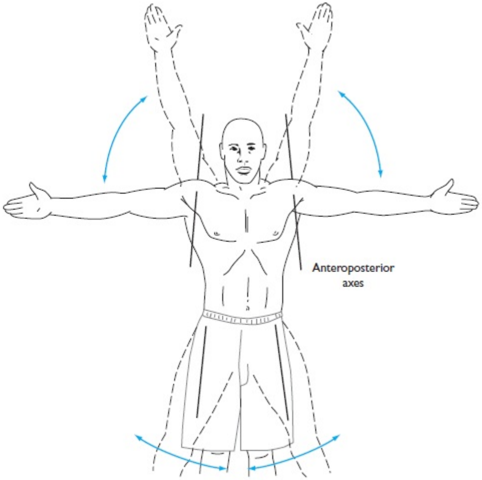
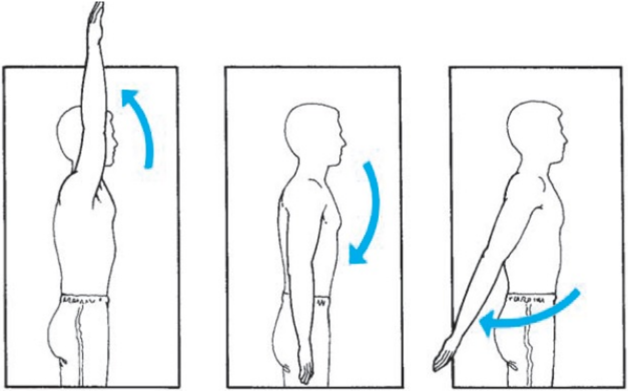
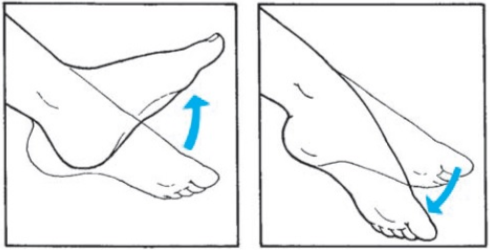


Kinematic concepts for analyzing human motion



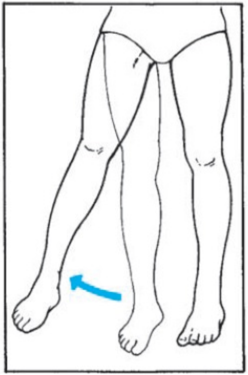
Flexion Extension Hyperextension

Kinematic concepts for analyzing human motion

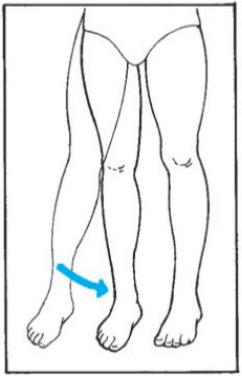


Dorsiflexion   Plantar flexion

Kinematic concepts for analyzing human motion

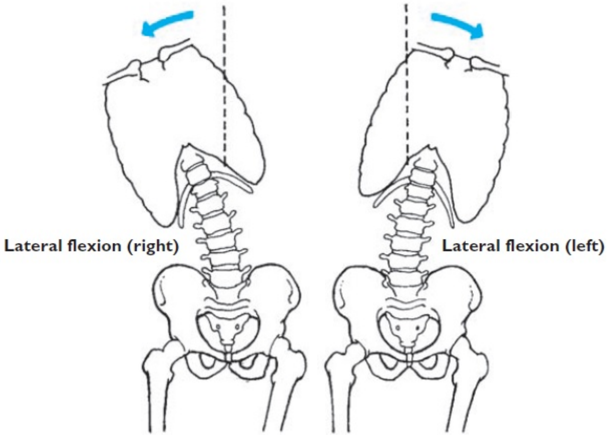


Abduction



Adduction

Kinematic concepts for analyzing human motion



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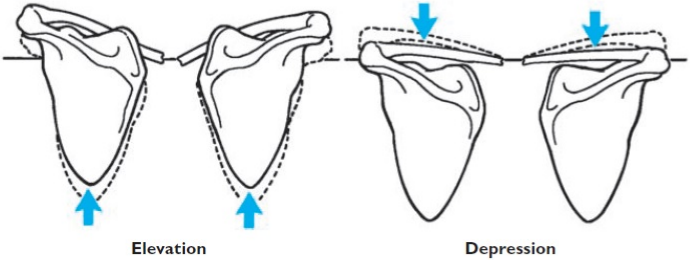

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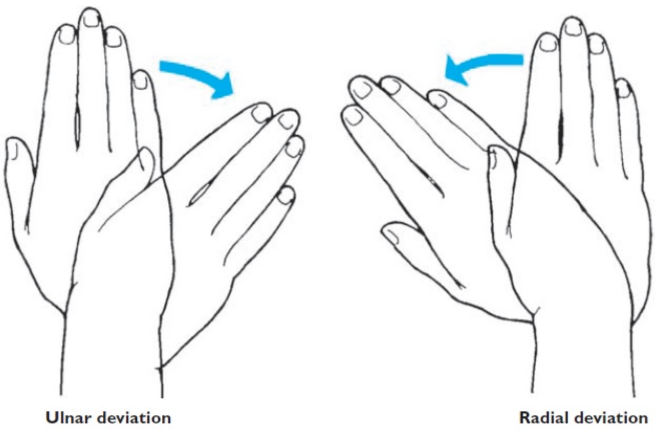

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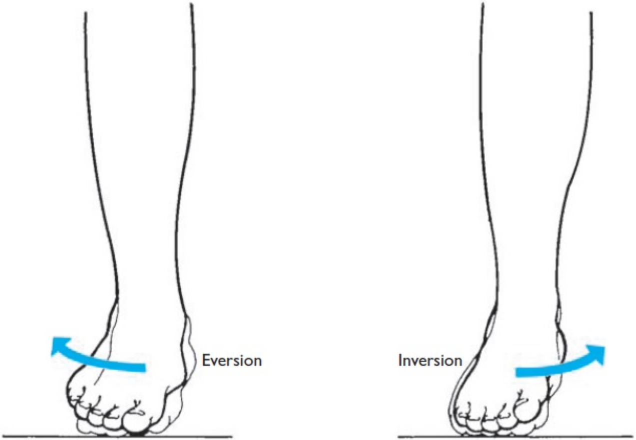

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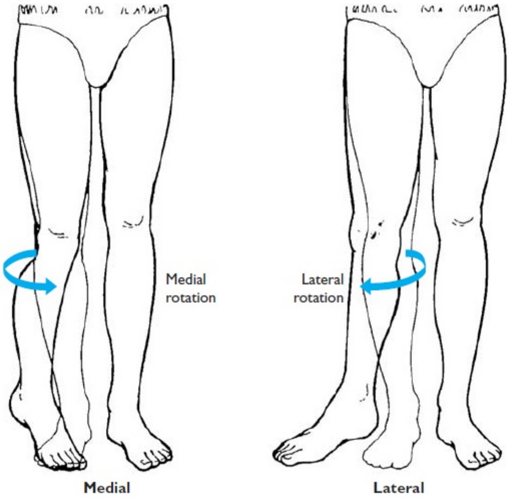

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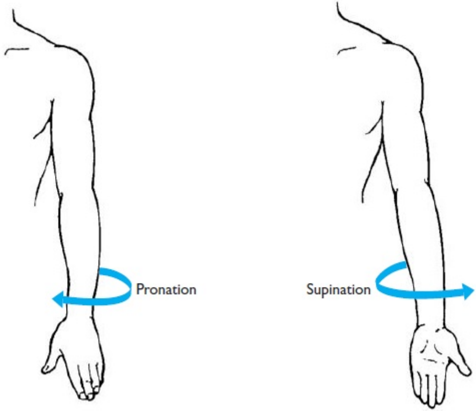

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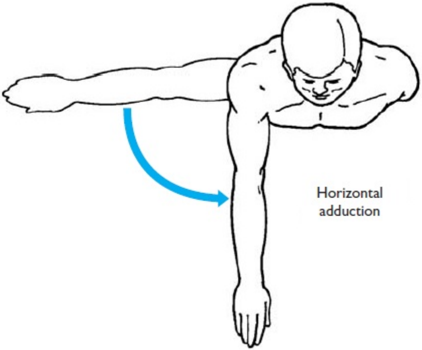

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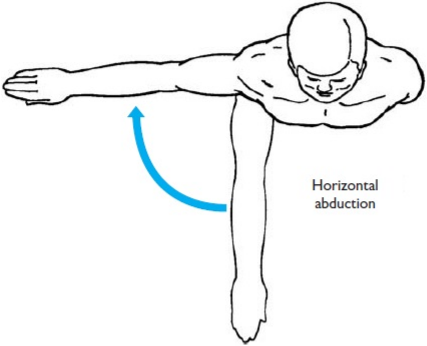
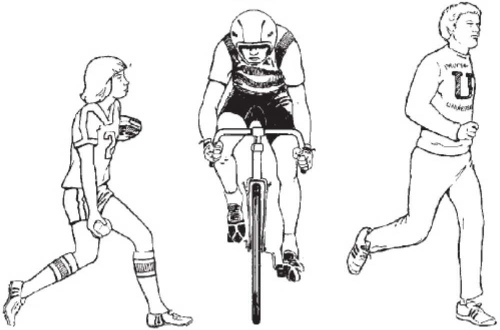


Kinematic concepts for analyzing human motion

Circumduction

Kinematic concepts for analyzing human motion

Primarily planar
skills



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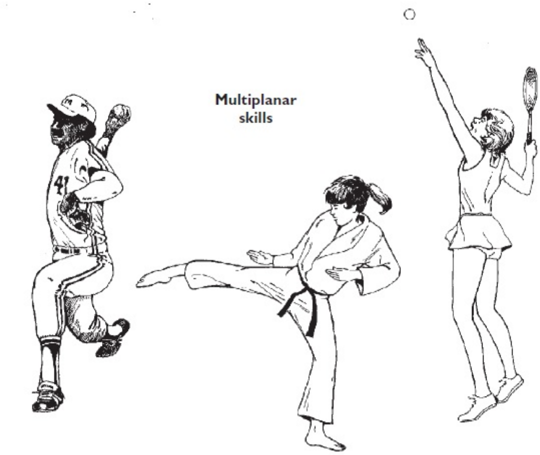

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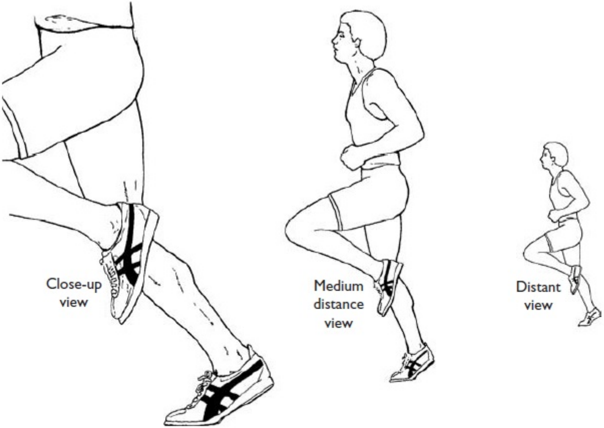
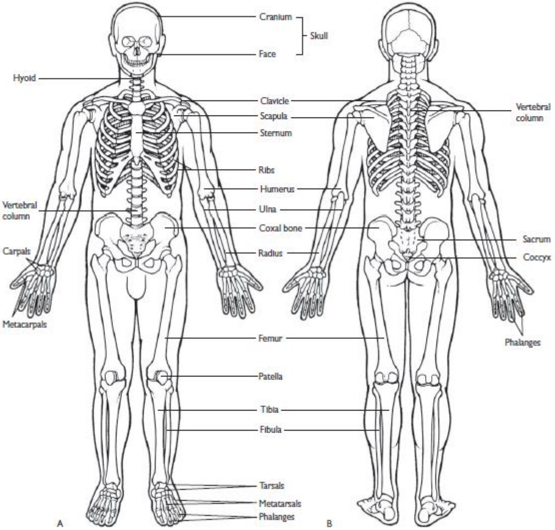


Types of Bones

Types of Bones



Types of Bones

- The structures and shapes of the 206 bones of the human body enable them to fulfill specific functions.The skeletal system is nominally subdivided into the central or axial skeleton and the peripheral orappendicular skeleton
- The axial skeleton includes the bones that form the axis of the body, which are the skull, the vertebrae,the sternum, and the ribs.
- The other bones form the body appendages, or the appendicular skeleton.

Types of Bones

- Bones are also categorized according to their general shapes and functions.

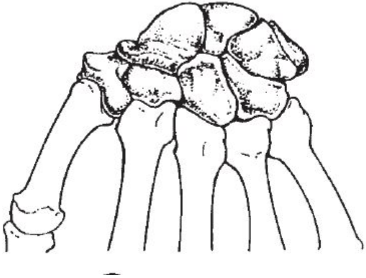
Types of Bones

Short bones , which are approximately cubical, include only the carpals and the tarsals

- These bones provide limited gliding motions and serve as shock absorbers.

Types of Bones

A



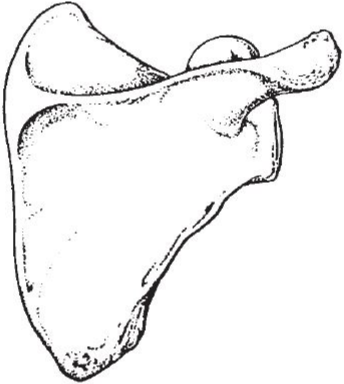
Types of Bones

Flat bones are also described by their name.

- These bones protect underlying organs and soft tissues and also provide large areas for muscle and ligament attachments.
- The flat bones include the scapulae, sternum, ribs, patellae, and some of the bones of the skull.

Types of Bones

B



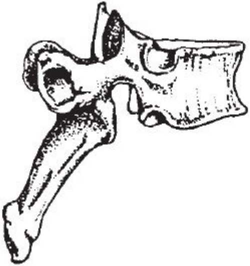
Types of Bones

Irregular bones have different shapes to fulfill special functions in the human body.

- For example, the vertebrae provide a bony, protective tunnel for the spinal cord;
- offer several processes for muscle and ligament attachments; and support the weight of the superior body parts while enabling movement of the trunk in all three cardinal planes.
- The sacrum, coccyx, and maxilla are other examples of irregular bones.

Types of Bones

c



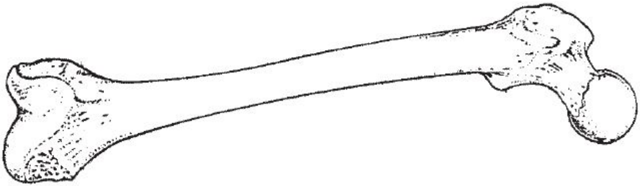
Types of Bones

Long bones form the framework of the appendicular skeleton.

- They consist of a long, roughly cylindrical shaft (also called the body, or diaphysis) of cortical bone, with bulbous ends known as condyles, tubercles, or tuberosities.

Types of Bones

D



Common Bone Injuries

Common Bone Injuries

A *greenstick* fracture is incomplete, and the break occurs on the convex surface of the bend in the bone.

Common Bone Injuries

A *fissured* fracture involves an incomplete longitudinal break.

Common Bone Injuries

A *comminuted* fracture is complete and fragments the bone.

Common Bone Injuries

A *transverse* fracture is complete, and the break occurs at a right angle to the axis of the bone.

Common Bone Injuries

An *oblique* fracture occurs at an angle other than a right angle to the axis of the bone.

Common Bone Injuries

A *spiral* fracture is caused by twisting a bone excessively.

Fractures

- A fracture is a disruption in the continuity of a bone.
- The nature of a fracture depends on the direction, magnitude, loading rate, and duration of the mechanical load sustained, as well as the health and maturity of the bone at the time of injury.
- Fractures are classified as simple when the bone ends remain within the surrounding soft tissues and compound when one or both bone ends protrude from the skin.

Immovable joints

Immovable joints

Synarthroses (immovable) (syn = together; arthron =joint):

These fibrous joints can attenuate force (absorb shock) but permit little or no movement of the articulating bones.

Immovable joints

Sutures: In these joints, the irregularly grooved articulating bone sheets mate closely and are tightly connected by fibers that are continuous with the periosteum.

- The fibers begin to ossify in early adulthood and are eventually replaced completely by bone.
- The only example in the human body is the sutures of the skull.

Immovable joints

Syndesmoses (syndesmosis = held by bands): In these joints, dense fibrous tissue binds the bones together, permitting extremely limited movement.

- Examples include the coracoacromial, mid-radioulnar, mid-tibiofibular, and inferior tibiofibular joints.

Slightly movable joints

Slightly movable joints

Amphiarthroses (slightly movable) (amphi = on both sides): These cartilaginous joints attenuate applied forces and permit more motion of the adjacent bones than synarthrodial joints.

Synchondroses (synchondrosis = held by cartilage): In these joints, the articulating bones are held together by a thin layer of hyaline cartilage.

- Examples include the sternocostal joints and the epiphyseal plates (before ossification).

Symphyses: In these joints, thin plates of hyaline cartilage separate a disc of fibrocartilage from the bones. Examples include the vertebral joints and the pubic symphysis.

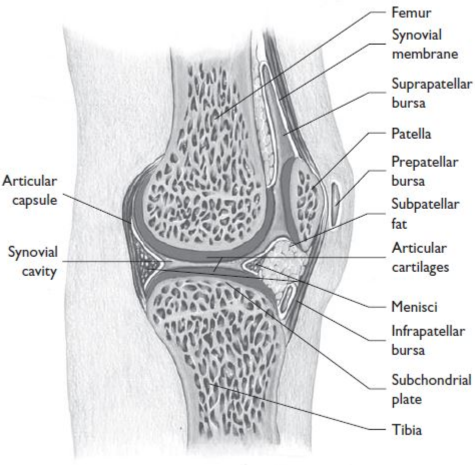
Freely movable joints

Freely movable joints

Diarthroses or synovial (freely movable) (diarthrosis = through joint, indicating only slight limitations to movement capability): At these joints, the articulating bone surfaces are covered with articular cartilage, an articular capsule surrounds the joint, and a synovial membrane lining the interior of the joint capsule secretes a lubricant known as synovial fluid.

- There are many types of synovial joints.

Synovial Joint : Knee Joint

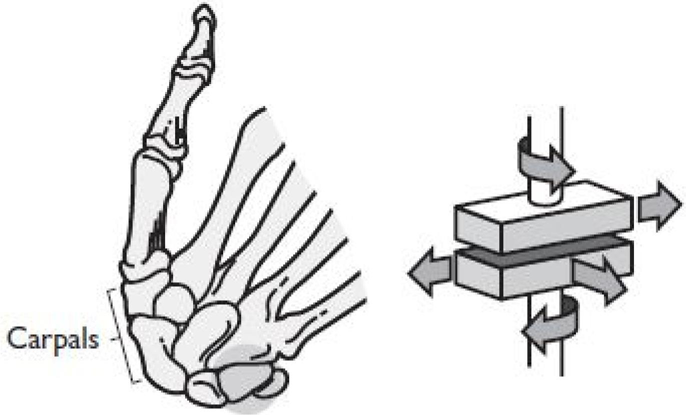


Freely movable joints

Gliding (plane; arthrodial): In these joints, the articulating bone surfaces are nearly at, and the only movement permitted is nonaxial gliding.

- Examples include the intermetatarsal, intercarpal, and intertarsal joints, and the facet joints of the vertebrae.

Gliding Joint



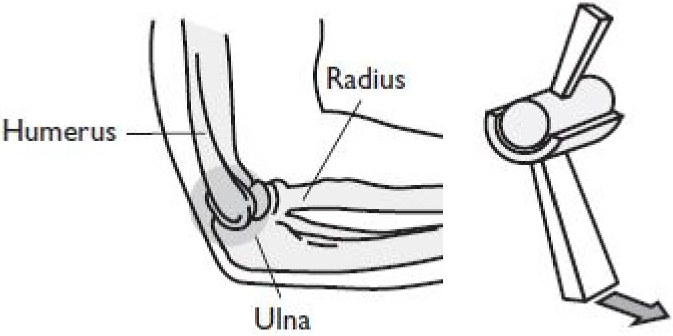
C **Gliding joint**

Freely movable joints

Hinge (ginglymus): One articulating bone surface is convex and the other is concave in these joints.

- Strong collateral ligaments restrict movement to a planar, hingelike motion.
- Examples include the ulnohumeral and interphalangeal joints.

Hinge Joint



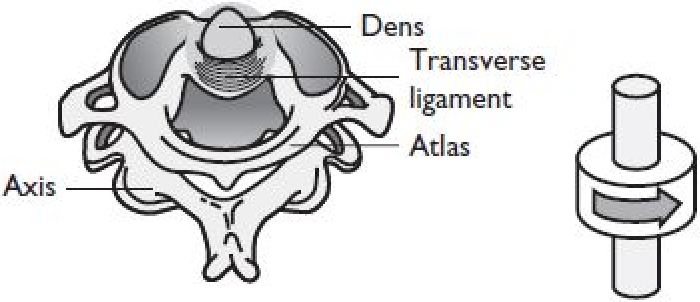
D **Hinge joint**

Freely movable joints

Pivot (screw; trochoid): In these joints, rotation is permitted around one axis.

- Examples include the atlantoaxial joint and the proximal and distal radioulnar joints.

Pivot Joint



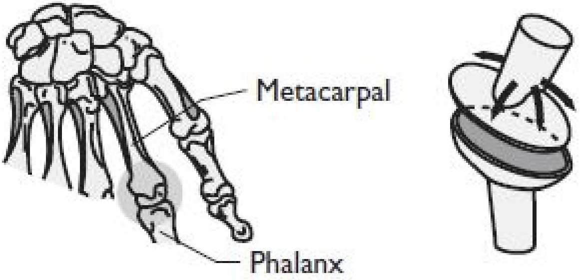
E Pivot joint

Freely movable joints

Condyloid (ovoid; ellipsoidal): One articulating bone surface is an ovular convex shape, and the other is a reciprocally shaped concave surface in these joints.

- Flexion, extension, abduction, adduction, and circumduction are permitted.
- Examples include the second through fifth metacarpophalangeal joints and the radiocarpal joints.

Condyloid Joint



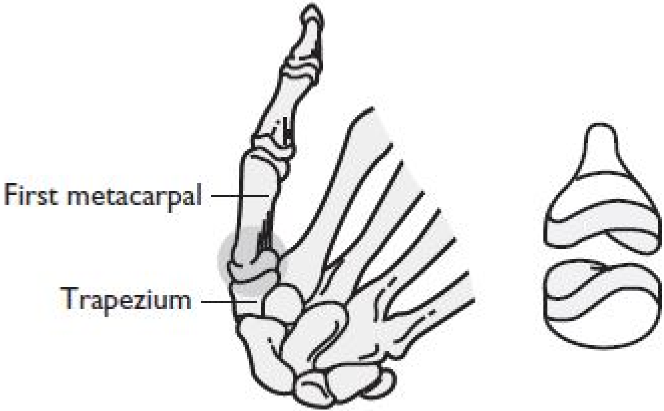
B Condyloid joint

Freely movable joints

Saddle (sellar): The articulating bone surfaces are both shaped like the seat of a riding saddle in these joints.

- Movement capability is the same as that of the condyloid joint, but greater range of movement is allowed.
- An example is the carpometacarpal joint of the thumb.

Saddle Joint



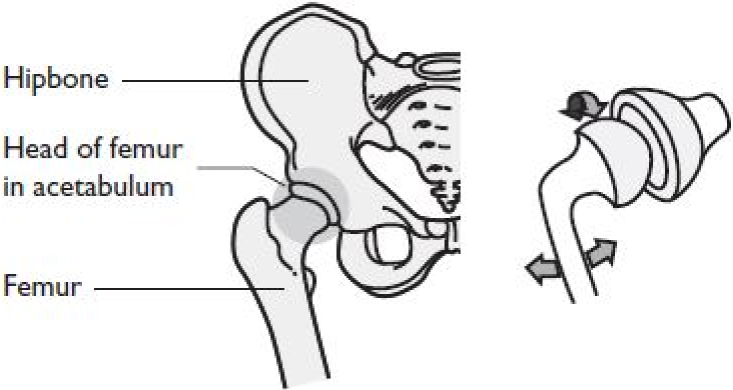
F Saddle joint

Freely movable joints

Ball and socket (spheroidal): In these joints, the surfaces of the articulating bones are reciprocally convex and concave.

- Rotation in all three planes of movement is permitted.
- Examples include the hip and shoulder joints.

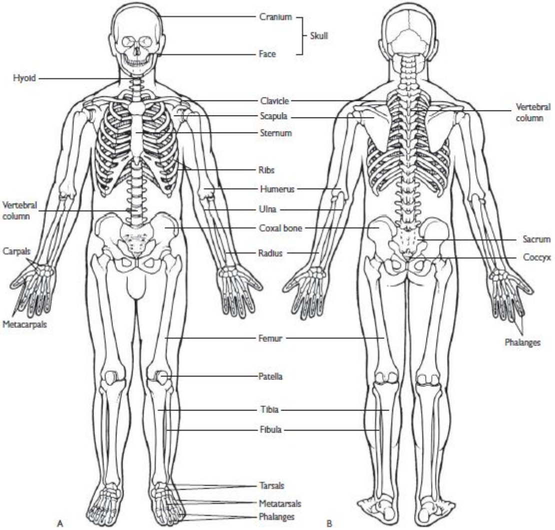
Ball and Socket Joint



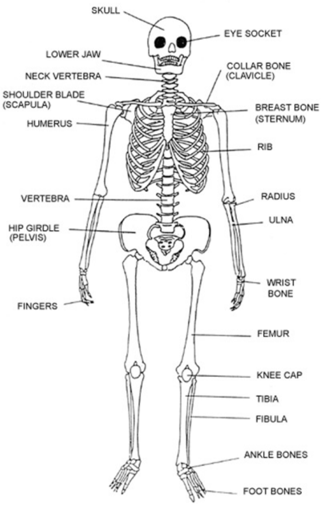
A Ball-and-socket joint

Motion Analysis

Human skeleton



Model building



Step 1: Generation of the Body Segments

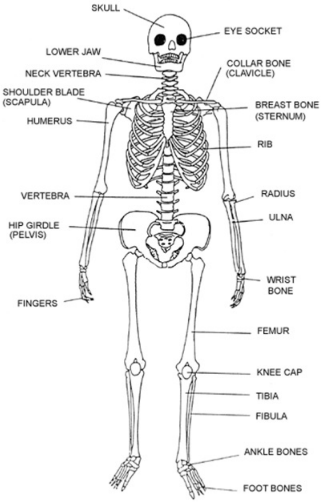
Step 2: Generation of the Joints

Step 3: Generation of the Muscle Forces

Step 4: Posing the Human Model

Step 5: Creating Contact Forces between the Human and the Environment

Model building



Step 6: Performing Inverse-Dynamics Simulations to calculate forces in muscles.

Step 7: Performing Forward-Dynamics Simulations using muscle forces

Step 8: Tune model parameters and rerun

Step 9: Reviewing the Simulation Results

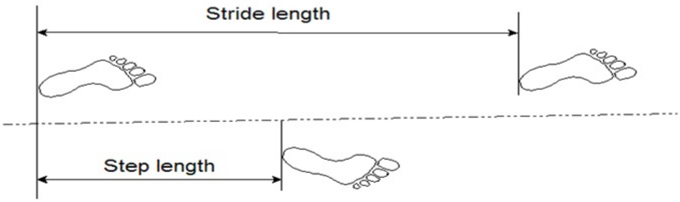
Running

- Flight phase
- One foot takes off before the other lands
- The rear foot takes off before the front foot lands

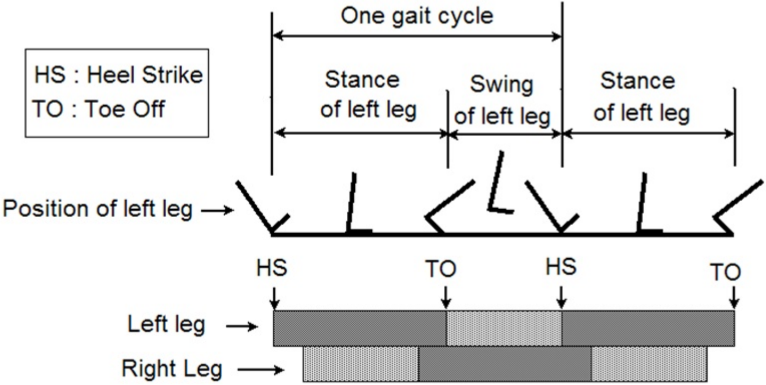
Walking

- Feet overlapping
- One foot lands up before the other foot takes off
- The heel of the front foot must touch the ground before the toe of the rear foot is lifted

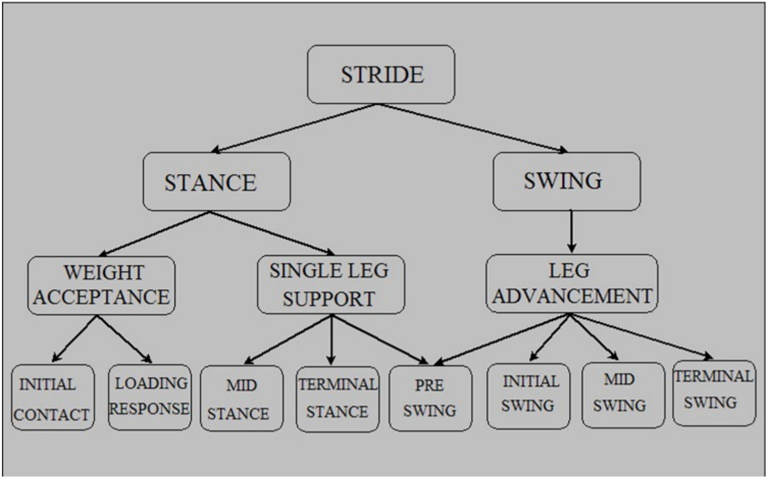
Human Gait



Human Gait


HS : Heel Strike
TO : Toe Off
One gait cycle
Stance
of left leg
Swing
of left leg
Stance
of left leg
Position of left leg
HS
TO
HS
TO
Left leg
Right Leg

Human Gait



STRIDE
STANCE
SWING
WEIGHT ACCEPTANCE
SINGLE LEG SUPPORT
LEG ADVANCEMENT
INITIAL CONTACT
LOADING RESPONSE
MID STANCE
TERMINAL STANCE
PRE SWING
INITIAL SWING
MID SWING
TERMINAL SWING

Normal Walking

Equilibrium : the ability to assume an upright posture and maintain balance.

Locomotion : the ability to initiate and maintain rhythmic stepping

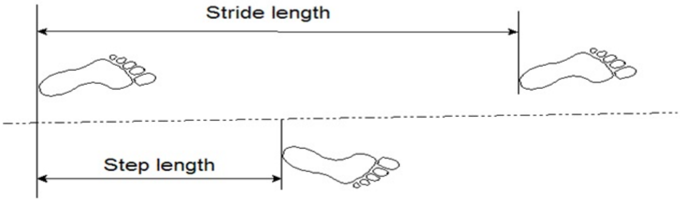
Gait disorder

- Due to pain
- Paralysis
- Damage of tissues
- Loss of motor control

Why study normal gait?

- One must have sound knowledge of the characteristics of normal gait so that the deviations from the normal gait is accurately detected and interpret

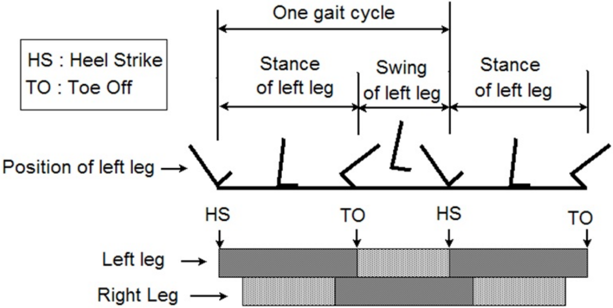
Gait Terminology



Step Length : Distance from one foot strike to the next, i.e. left to right OR right to left

Stride Length : Distance between two successive placements of the same foot,i.e. two successive steps (by both left and right feet)

Gait Cycle

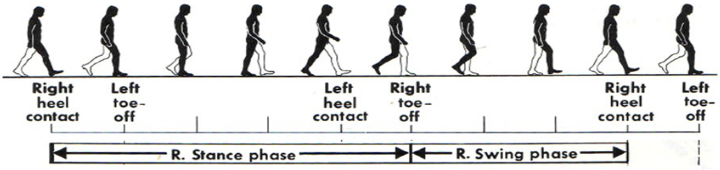


Stance : period when the foot is in contact with the ground (60-62% of gait cycle)

Swing : period when the foot is off the ground (about 38-40% of gait cycle)

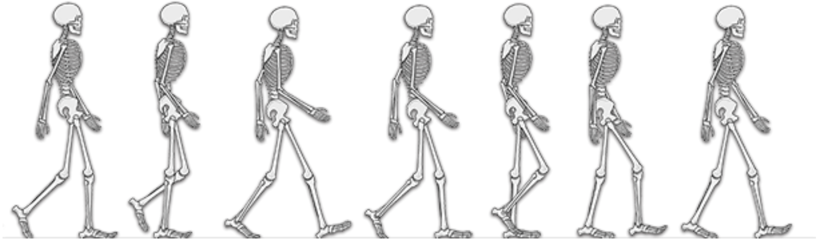
Double Support : period when both feet are on the ground (10-12% of gait cycle)

Gait Cycle



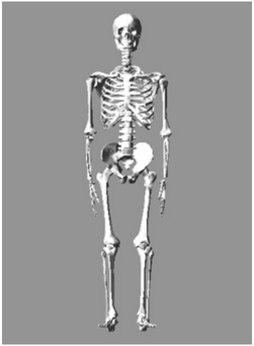
http://www2.warwick.ac.uk/fac/sci/eng/meng/nongps/rnd/gait/

Gait Cycle

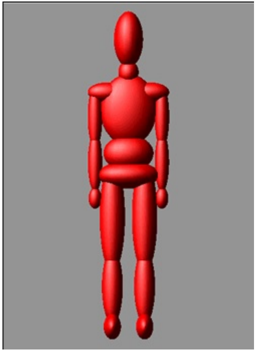


http://www.gcmas.org/

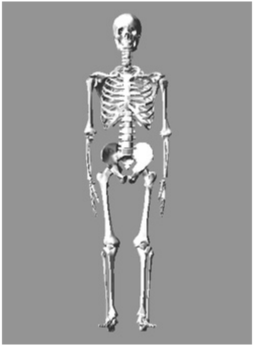
Skeletal Modelling of Human Body

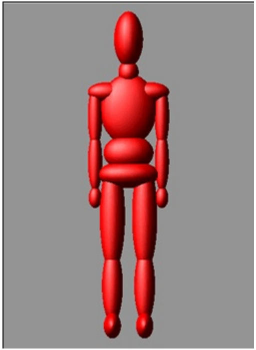


Skeletal Modelling of Human Body



Skeletal Modelling of Human Body





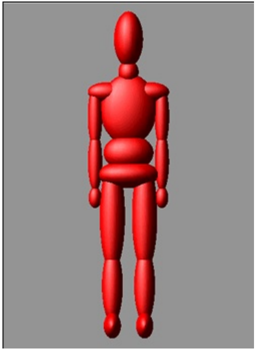
Skeletal Modelling of Human Body

- Left Scapular
- Left Upper Arm
- Left Lower Arm
- Left Hand
- Left Upper Leg
- Left Lower Leg
- Left foot

- Head
- Neck
- Upper Torso
- Central Torso
- Lower Torso

- Right Scapular
- Right Upper Arm
- Right Lower Arm
- Right Hand
- Right Upper Leg
- Right Lower Leg
- Right foot

Skeletal Modelling of Human Body



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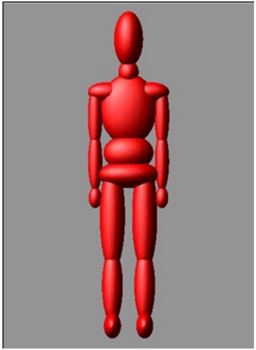

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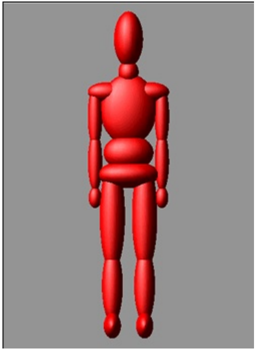

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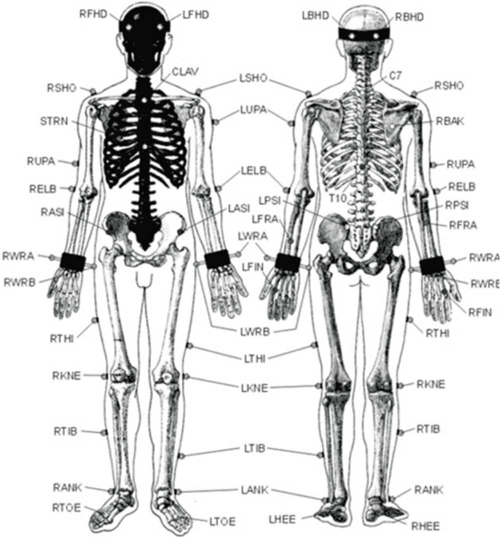
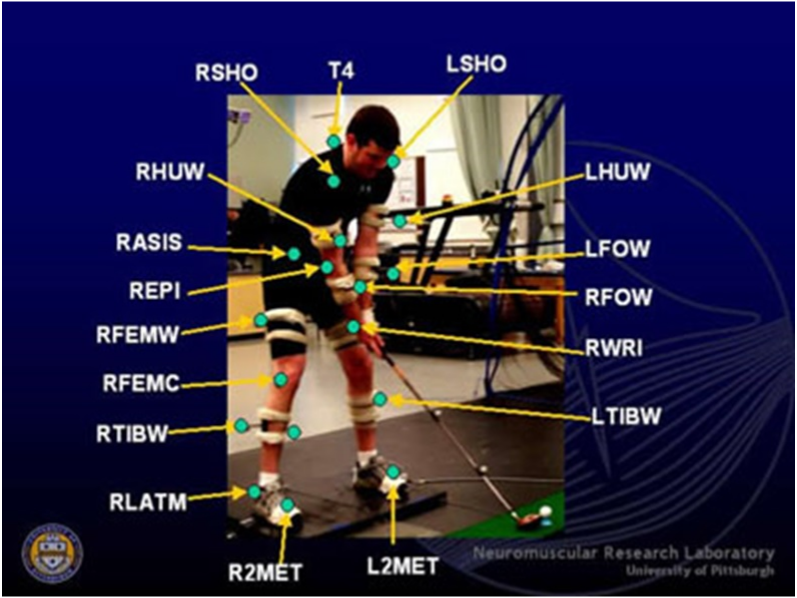
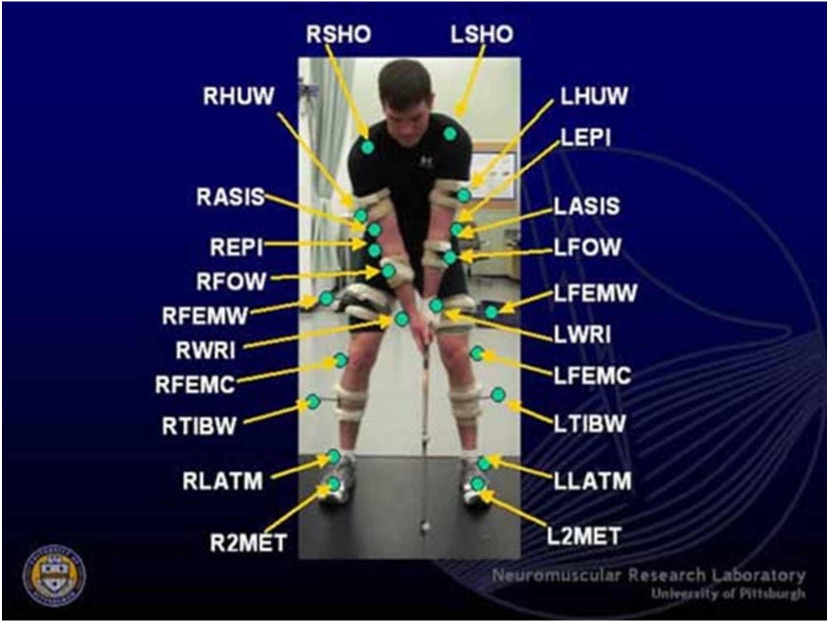
Motion Marker



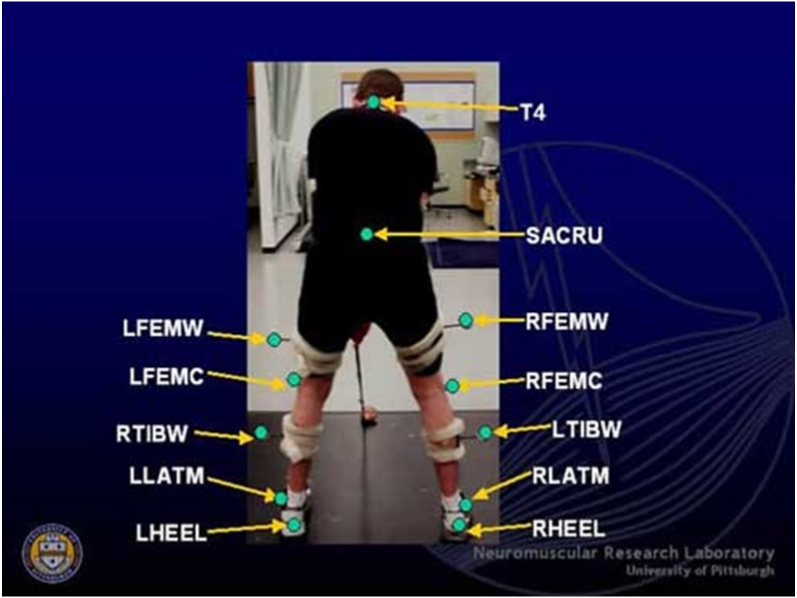
Motion Marker



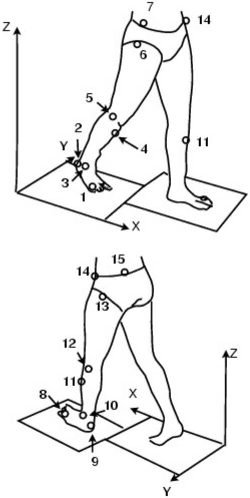
Motion Marker



Motion Marker



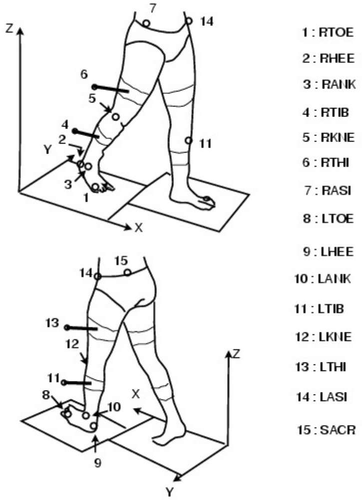
Gait Marker : Kit Vaughan Gait Model



- 1 : RTOE
- 2 : RHEE
- 3 : RANK
- 4 : RTIB
- 5 : RKNE
- 6 : RTHI
- 7 : RASI
- 8 : LTOE
- 9 : LHEE
- 10 : LANK
- 11 : LTIB
- 12 : LKNE
- 13 : LTHI
- 14 : LASI
- 15 : SACR

1, 8	Right and Left Metatarsal Head V
2, 9	Right and Left Heel
3, 10	Right and Left Malleolous
4, 11	Right and Left
	Tibial Tubercle
5, 12	Right and Left
	Femoral Epicondyle
6, 13	Right and Left
	Greater Trochanter
7, 14	Right and Left ASIS
15	Sacrum

Gait Marker : Helen Hayes Gait Model



1, 8	Right and Left Metatarsal Head II
2, 9	Right and Left Heel
3, 10	Right and Left Malleolous
4, 11	Right and Left
	Tibial Wand
5, 12	Right and Left
	Femoral Epicondyle
6, 13	Right and Left
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7, 14	Right and Left ASIS
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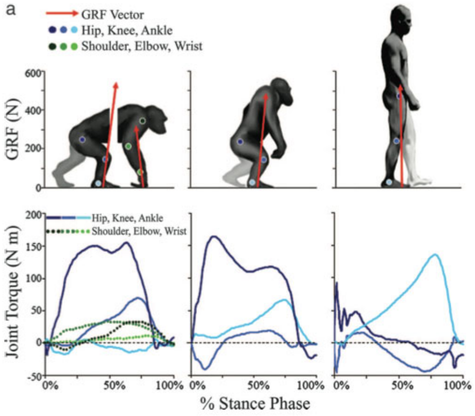
Comparison of walking mechanics of chimpanjees and humans



https://anthropology.net/comparison-of-walking-mechanics-in-chimpanzees-and-humans/

Dynamics of Some Games and Sports

Dynamics of Some Games and Sports

- A rough estimates of the relevant physical quantities involved in walking, running, jumping, cycling, throwing, swimming, etc. can be found out by simple dynamics

Dynamics of Some Games and Sports

- First of all we must know the basic physical statistics of an average athlete.

Physical Statistics of an Average Athlete

Mass of the body (M): This is an essential quantity, which is taken to be 50 kg, unless otherwise stated.

- The centre of mass of the body lies quite close to one's navel, the average position being about 5 cm below the navel and about as much inside the body.
- The average density of the body is minimally less than that of water, except for the head.

Physical Statistics of an Average Athlete

Surface area of the body (A): The knowledge of this quantity for different parts of the body is essential for different types of sports activities, but it is not at all easy to estimate with great accuracy.

- Perhaps one can take a wide roll of nonsticking bandage cloth, wrap it around the whole body without overlap and estimate the total surface area to an accuray on the order of 1%.
- In order to reach a 5% accuracy, one can divide the whole body broadly into 4 sections - head and neck, trunk, hands and legs, assuming their shapes roughly as spheres or, cylinders or, truncated cones as the case may be.

Physical Statistics of an Average Athlete, surface area

- At a still more crude level, the area of the whole body can be taken as approximately three times the area of the trunk.

Physical Statistics of an Average Athlete, surface area

- A widely used formula seems to be
  - $A = (M/30kg)^{0.7} metre^2$ for male
  - $A = (M/33kg)^{0.7} metre^2$ for female
- replaced 30kg by 33kg

Physical Statistics of an Average Athlete, surface area

- The proportional distributions for head and neck : trunk : hands : legs ratios for an athelete is given below

	Mass	Surface area
Male	0.07 : 0.57 : 0.09 : 0.27	0.09 : 0.33 : 0.20 : 0.38
Female	0.07 : 0.52 : 0.07 : 0.34	0.09 : 0.31 : 0.17 : 0.43

Physical Statistics of an Average Athlete

Principal moments of inertia of the body about its centre of mass (I_{xx}, I_{yy}, I_{zz}) for different symmetric configurations.

- The body frame axes x , y, z are defined as follows:

  x-axis: back to front (horizontal forward) about which cartwheeling is performed

  y-axis: right to left (horizontal sidewise) about which somersault is performed

  z-axis: bottom to top (vertically upward) about which twist is performed.

Moments of Inertia of Human Body under Different Configurations

Configuration	Layout, arms at sides	Layout, arms overhead	Layout, arms out	Layout, twists thrown	Relaxed
$I_{xx}(kgm^2)$	13.5	17.9	16.6	15.0	10.8
$I_{yy}(kgm^2)$	12.0	16.0	13.3	13.5	10.3
$I_{zz}(kgm^2)$	01.5	01.5	03.5	01.3	04.4

Body's rate of expenditure of energy

- There are basically two types of food as well as replenishable material in our body that are capable of delivering energy to or out from the body.
- One is fat (oily substances) with its calorie value 7700 Cal/kg (1 Cal = 1000 cal = 4200 J)
- The other is carbohydrate with its calorie value 3500 Cal/kg.
- It means that if you eat 100 gm of any oil/fat or 220 gm of sugar/ carbohydrate you gain about 770 Cal,
- If you work physically worth 770 Cal you will lose 22Q gm sugar content or 100 gm of body's stored fat in case sugar is not readily available.
- Let's see the energy expenditure rate (K) for various activities in Cal/hr/kg of bodyweight

Body's rate of expenditure of energy

- In total, a typically hard-working person accounts for a daily expenditure rate of energy of about 30 Cal/kg of bodyweight on various activies
- The other major losses are due to required supply of heat of evaporation of sweat and the heat loss of the body to the surroundings in order to maintain the temperature difference between the body and the immediate surrounding.

Power Consumption in various Human Activities

Activity	K (Cal/hr/kg)	Type
Sleeping	1.00	Slow
Sitting still	1.30	Slow
Standing relaxed	1.55	Slow
Dressing/undressing	1.75	Slow
Walking (4.5 km/hr)	3.30	Fast
Fast walking(6.5 km.hr)	4.40	Fast
Going down steps	5.0	Fast
Going up steps	15.	Fast

Power Consumption in various Human Activities

Activity	K (Cal/hr/kg)	Type
Light exercise	2.75	Slow
Active exercise	4.2	Fast
Heavy exercise	6.0	Fast
Very heavy exercise	9.0	Fast

Power Consumption in various Human Activities

Activity	K (Cal/hr/kg)	Type
Sewing by hand	1.65	Slow
Singing	1.85	Slow
Typewriting	2.00	Slow
Washing dishes	2.10	Slow
Sweeping	2.20	Slow
Carpentry	3.8	Fast
Loading heavy objects	5.5	Fast
Tennis play / swimming	7.2	Fast

Strolling or Leisurely Walking

Strolling or Leisurely Walking

- When one walks in a leisurely fashion, one does not exert much effort consciously.
- The process of such walking can be approximated to the natural pendulum-like oscillations of the legs about the respective hip joints.
- If the centre of mass of the legs of length L lies a distance d below the hip joint and the two legs make a maximum angle 2θ at the apex during walking, the half period of oscillation of the legs is simply :

$$T_0 = \pi\sqrt{\frac{d}{g}} \tag{1}$$

Strolling or Leisurely Walking

- During this time, the person moves through a distance x_0, the length of stride,

$$x_0 = 2Lsin\theta \tag{2}$$

- Thus the average speed of walking leisurely is

$$V_0 = \frac{x_0}{T_0} = \frac{2Lsin\theta}{\pi}\sqrt{\frac{g}{d}} = \frac{2}{\pi}\sqrt{\frac{gL}{\lambda}}sin\theta \tag{3}$$

- where λ is defined through $d = \lambda L$, $\lambda < 0.5$.

Strolling or Leisurely Walking

$$V_0 = \frac{x_0}{T_0} = \frac{2L sin\theta}{\pi}\sqrt{\frac{g}{d}} = \frac{2}{\pi}\sqrt{\frac{gL}{\lambda}} sin\theta \tag{4}$$

- Therefore,
  (i) the longer the legs the faster is the speed of walking,
  (ii) the bigger the stride the faster is the speed,
  (iii) the speed is independent of the weight of the body,
  (iv) walking on the surface of the moon will be about 2.5 titnes slower than that on earth, because of the reduced g-factor.

Strolling or Leisurely Walking

$$V_0 = \frac{x_0}{T_0} = \frac{2Lsin\theta}{\pi}\sqrt{\frac{g}{d}} = \frac{2}{\pi}\sqrt{\frac{gL}{\lambda}}sin\theta \qquad (5)$$

- Taking $\lambda = 0.4$ $L = 0.8m$, and small θ, one gets

$$v_0 = 2.8 \times \theta,\ \ m/s \approx 10 \times \theta\ \ km/hr \qquad (6)$$

- If $\theta \approx 15^\circ$ $v_0 \approx 2.6$ km/hr.

Strolling or Leisurely Walking

- Now when the two legs are farthest apart (2θ), the centre of gravity of the body is lowered by $h = L(I - cos\theta) = 2Lsin^2(\theta/2)$
- So the work done in walking through a total distance D is given by

$$W_0 = Mgh\left(\frac{D}{2Lsin\theta}\right) \approx \frac{MgD\theta}{4} \qquad (7)$$

- So the total work done is proportional to the distance walked as well as to the length of stride or the speed of walking.

Race Walking

Race Walking

- The difference between walking and running is that, in walking either of the legs must continue to keep in touch with the ground.
- As one tends to walk fast, one moves the legs with conscious effort and the motion can no longer be approximated to the natural oscillation of the legs.
- In race walking the objective is to increase the speed of walking to the maximum extent.

Race Walking

- For leisurely walking, the equation of motion is :

$$V_0 = \frac{x_0}{T_0} = \frac{2Lsin\theta}{\pi}\sqrt{\frac{g}{d}} = \frac{2}{\pi}\sqrt{\frac{gL}{\lambda}}sin\theta \tag{8}$$

- The above equation suggests that the increase of speed can be achieved by increasing the length of stride or θ.
- But as θ increases, the total vertical amplitude of the up and down motion of the CM, that is, h increases as θ^2, and the requirement of power also increases as θ^2
- For a stride length of about $\theta = 30^\circ$, the waddling amplitude of the CM from the above formula becomes as high as 10.7 cm for L $=$ 0.8 m.

Race Walking

- During fast walking, the legs begin to bend forward sufficiently at the knees, the CM begins to experience a free fall through a height of h, and the time interval T_0 between the strides is approximately given by

$$T_0 = 2\sqrt{\frac{2h}{g}} \tag{9}$$

- with the exception that for bent legs, the expression for h can no longer be given by $h = L(I - cos\theta)$

Race Walking

$$T_0 = 2\sqrt{\frac{2h}{g}} \tag{10}$$

- Keeping h as a free parameter, the speed of race walking now becomes
$$v_0 = \frac{2Lsin\theta}{T_0} = Lsin\theta\sqrt{\frac{g}{2h}} \tag{11}$$
- The above equation suggests that the athlete cannot increase the speed of his/her race walking without increasing θ or decreasing h, which under normal circumstances does not go in the desired opposite way.
- Moreover, for $\theta = 30^\circ$, L $=$ 0.8 m, and $v_0 = 5$m/s ($=$ 18 km/hr), the required value of h must not exceed 3 cm!

Race Walking

- Therefore, the art of race walking is to learn how not to allow the waddling of the CM increase with the increase of the length of stride.
- This is accomplished by athletes with a calculated movement of their hips which is fast enough to arrest the rapid free fall of the CM of the whole body but slow enough for throwing their legs to have as big a stride as possible.

Maximum Speed of Running

Maximum Speed of Running

- A runner usually accerates in each stride in the beginning and in about a dozen strides achieves the full speed of running.
- Now each leg comes to rest for a while when it touches the ground.
- The kinetic energy of the trunk of the body continues with full speed once this maximum is achieved, but the leg's rotational kinetic energy about the feet and the hip joints vary alternately between zero and a maximum value of $I\omega_0^2/2$, where I is the average MI of the leg about either end and ω_0 is the maximum angular velocity of both the legs in each stride.

Maximum Speed of Running

- The constant supply of this energy comes from the work done by the thrust of reaction acting on the forward leg that rests on the ground and bends at the knee, and the force acts over a push-off length s of the bent leg.

Maximum Speed of Running

- If the maximum force available in the form of the thrust of reaction from the ground available is μ times the body's weight Mg,the energy equation simply gives

$$2 \times \frac{1}{2} I\omega_0^2 \leq \mu Mgs \tag{12}$$

- where ω_0 is given by

$$\omega_0 = \frac{v_0}{L} \tag{13}$$

- v_0 being the maximum speed of the runner and L being the length of each leg.
- Here the uncertain parameters are I,μ, and s.

Maximum Speed of Running

- However, one can perhaps take
$$I = \frac{1}{3} m_l L^2 \qquad \mu = 1.5 \qquad and \qquad \frac{M}{m_l} = 7 \;\; to \;\; 7.5 \;\; or \;\; 8 \tag{14}$$
- where m_l is the mass of each leg.
- For an estimate of s , which is approximately the separation between a fully extended leg and a bent one; or the distance through which the CM of the body moves while the leg is on the ground, one can assume the location of the knee to be at the middle point of the legand the maximum bending of the leg at the knee is as large as 90° , giving
$$s \approx \frac{(2-\sqrt{2})L}{2} \approx 0.3L \tag{15}$$

Maximum Speed of Running

- So finally we get, for an average athlete,

$$v_0 \leq \sqrt{3\left(1-\frac{1}{\sqrt{2}}\right)\mu g L\left(\frac{M}{m_l}\right)} \approx 8.7 m/s \tag{16}$$

- In order to increase the value of v_0 further, a professional runner must have longer ($L \approx 1m$) but lighter legs ($M/m_l \approx 8$, relatively longer forelegs compared to thigh (for achievinglarger value of s) and strong enough to produce larger thrust ($\mu \approx 1.5$) so that

$$v_0 \approx 10.2 \ m/s \tag{17}$$

- or in other words, for a 100 m run, the runner would take about 9.8 s.

Maximum Speed of Running

- However, using certain drugs such as steroids, one can illegally increase the strength factor μ , which was the reason for Mr. Ben Johnson's earning notoriety in the 100 m men's running event , in the 1988 Olympics.

Maximum Speed of Running

- Since the work done by the legs during each stride is $W_0 = \mu Mgs$ and the final kinetic energy of the .runner becomes
$$\frac{1}{2}Mv_0^2 = \frac{3}{2}\frac{\mu M^2 gs}{m_l} = \frac{3}{2}\left(\frac{M}{m_l}\right)W_o \approx (10-12)\times W_0 \qquad (18)$$
- It means that the runner can accelerate himself /herself to his/her maximum speed of running at the end of the first 10 - 12 strides.
- This is universally true for all runners, amateur or professional, as it depends simply on the ratio of M and m_l.

Maximum Range of Long Jump

Maximum Range of Long Jump

- Generally, at the end of about a dozen strides, the athlete gains the maximum speed of horizontal running.
- For a long jump (also called broad jump) the runner has to throw himself off the ground with an angle of elevation say θ_i in order to increase the range of his jump.

Maximum Range of Long Jump

- In absence of any drag, the horizontal range of the runner as a projectile is

$$R_l = \frac{V_0^2}{g} sin2\theta_i \tag{19}$$

- where V_0 is the speed just before taking off the ground
- Obviously, R_l is maximum for $\theta_i = \pi/4$, giving $R_l = V_0^2/g$.
- It may be noted that $dR_l/d\theta_i = 0$ for $\theta_i = \pi/4$, so achieving maximum value of R_l near $\theta_i = \pi/4$ is relatively insensitive to θ_i.
- For a range of θ_i between 40° and 50° , the variation of R_1 remains within about 2%.
- Putting $V_0 = 10$ m/s, $R_l = 10$m, and even if $\theta_i = 30^\circ$, R_l reduces only to 8.7m

Maximum Range of Long Jump

- It seems that the best runner would also succeed as the best champion of broad jump.
- The art of this game is to produce the right take off angle which should be no less than 30°
- The entire linear momentum of the body has to change its direction during the last stride only.
- It requires a special technique so that the last push off becomes sufficiently long.
- The vertical component of the momentum generated in the final push off has to be comparable to its horizontal component, the one that has been achieved in about 10 strides.
- Usually the runner lowers the level of his/her CG and thrusts himself/herself up and the duratiqn of the last push τ is made to be the longest possible one.

Maximum Range of Long Jump

- Now, after n (n $<$ 12) strides on the ground before the final one, the horizontal speed becomes

$$v_h = \sqrt{2n\mu g s} \tag{20}$$

- During the last stride the gain in the vertical component of the velocity can be approximated to

$$v_v = \mu g \tau = \mu g \frac{\beta L}{v_h} \tag{21}$$

- where β, defined through the above relation, corresponds to an effective length of the final stride.
- β can be treated as a constant only if $v_v >> 0$, which is true for broad jumps but not for high jumps.

Maximum Range of Long Jump

- Since $tan\theta_i = v_v/v_h$ and $V_0^2 = v_h^2 + v_v^2$,
- R_l can be computed as

$$\begin{aligned} R_l &= 2\mu\beta L \\ \theta_i &= tan^{-1}\left[\frac{\beta}{(2-\sqrt{2})n}\right] \end{aligned} \tag{22}$$

- The extra parameter β plays a crucial role in determining R_l apart from μ and L.
- The current world record of long jump $R_l \approx 8.95$ m requires a value of $\beta \approx 3$, and hence $\theta_i \approx 27^\circ$ for $n \approx 10$.

Maximum Height of Vertical Jump

Maximum Height of Vertical Jump

- In this game, it is the centre of gravity of the athlete that has to be lifted as high as possible by generating the maximum amount of the vertical component of the impulse using the maximum possible thrust received from the ground.
- The separation between the lifted CG and the reference horizontal bar (h') is also to be minimised.
- Knowing the CG of the upright body lies inside the body, but if the body is given a shape of an inverted 'V', the CG will not only come out of the body but also remain in a low position.
- It is known that one can topple over a horizontal fencing keeping the CG all the time slightly below the upper boundary of the fencing.
- So an athlete can in practice achieve $h' \leq 0$ in high jumps.

Maximum Height of Vertical Jump

- Suppose just before the final take off the athlete brings his/her CG down by a height $h_0\delta(\delta < 1)$ from its usual original height h_0
- Then the athlete exerts maximum possible thrust on the ground so that the force of reaction μMg begins to act on the body.
- It can continue to act so long as the feet remain on the ground, that is, the CG does not go off above its normal height h_0.
- Since the work done on the whole body is $\mu Mgh_0\delta$, after the take off the CG will continue to rise a further height of $\mu h_0\delta$.
- Hence the total height of the CG above the ground at its peak of climbing becomes

$$H + h' = h_0(1 + \mu\delta) \tag{23}$$

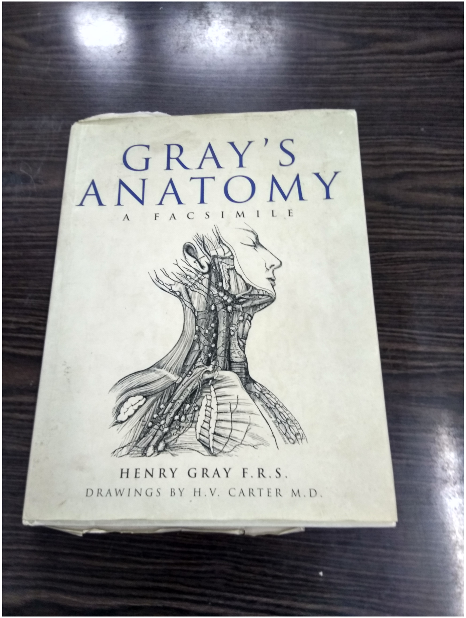
- where H is the height of the reference bar from the level of the ground.

Maximum Height of Vertical Jump

- For a typical athlete, $h_0 = 1m$, $\delta = 0.6, \mu = 1.5$ and $h' = 0$, thus giving
$$H = 1.9 \ m \tag{24}$$
- By stretching all the parameters to the extreme, one can perhaps achieve $h_0 = 1.1$m,$\delta = 0.75$, $\mu = 1.6$, $h' = -0.05$ m in which case H $=$ 2.47 m,
- The present world record of high jump being 2.45 m, held by Javier Sotomayor of Cuba.
- The interesting point to note is that in the equation
$$H + h' = h_0(1 + \mu\delta \tag{25}$$
- the value of g scales out from both sides, and therefore, the statistics of high jump will hardly improve on any other celestial object where the value of g is markedly different, except that the value of the μ factor might be substantially higher in conditions of lower gravity.

Books

Book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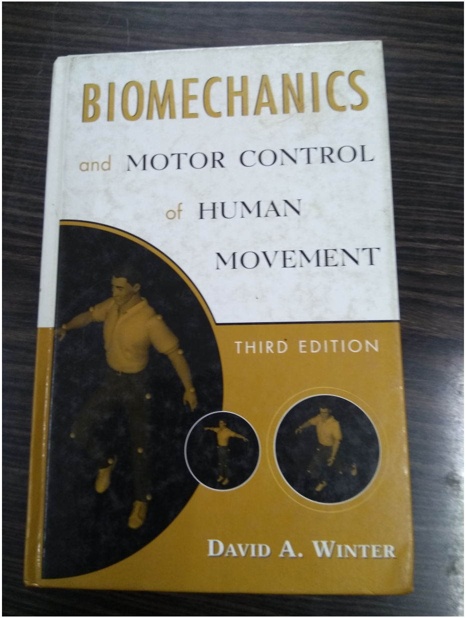
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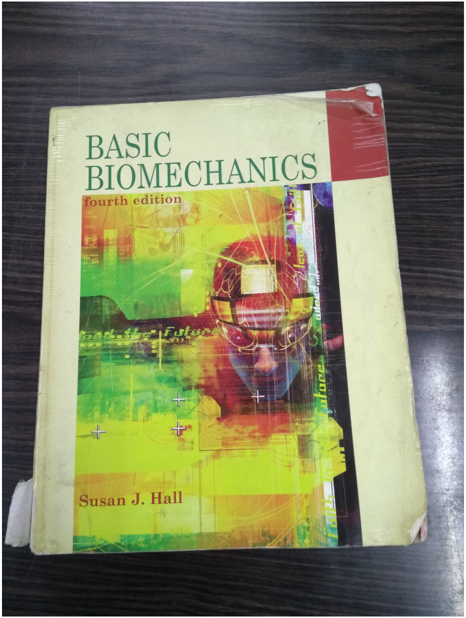

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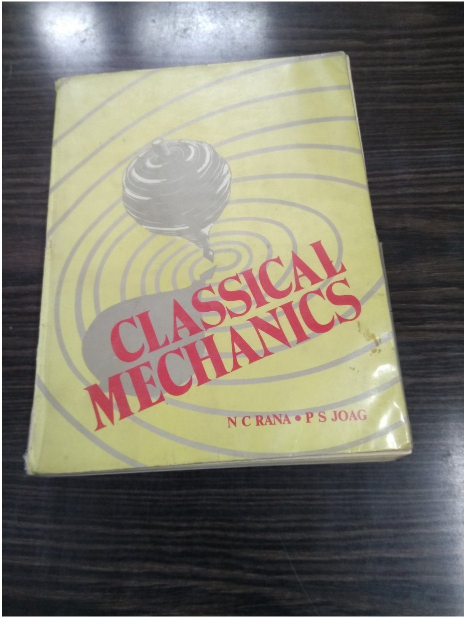

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