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SPORTS HINTS FROM THE SKELETON AND THE WEIGHT BEARING JOINTS

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ABSTRACT
Various sports demand efficient activity of the trainee. Guidance is the responsibility of the trainers. This is an endless ocean of information and practice. We have tried here to highlight a very simple clue from the anatomy and tried to analyze it mathematically. It can be shown that simple X-ray of hip will give an idea about the disposition of the head and neck of femur in a particular case which can guide the observer about the 'cone' and the semi-vertical angles at the 'center of rotation'(CR). The intensity of force transmission increases as the semi-vertical angle decreases (figs. 8-10). Here we can say force / body-weight has a tendency to concentrate to very small area which is essential for a sprinter as very small area of contact is needed through which body-weight pass and reaction of ground will act oppositely by Newton's Third law of motion. But for a weight-lifter distribution of force i.e. flatness of force / body-weight is required. Also, heat dissipation from the hyper-active joints during sports activities require proper understanding for the choice of the particular category of sport.

INTRODUCTION
Pelvis and the hip joints together act like the supporting base at the bottom of the torso. The lower limbs having knee, ankle and the small joints of the feet act like props. Sports activity of a person is guided by all these structures. The shape, alignment and the micro-structure of the bone around the weight bearing joints have to be considered carefully to assess the efficiency and future possibility of improvement.

Key Words: *Weight Bearing Joints, Mathematical Analysis Of Advantages In Sports*

MATERIALS AND METHODS
Ordinary state X-rays of hip have been considered for our study and mathematical tools have been used to explain the know-how.

RESULTS AND DISCUSSION
Clinical examination and ordinary x-ray study can help the sports aspirant. Weight lifting requires stability, running requires mobility. Efficient bio-mechanical design can determine mobility at the cost of stability. Mobility often raises heat at the joints which requires efficient cooling system for satisfactory performance in the long run.
Nature has not provided any blood vessel in the joint cartilage which could then create heat due to the flow of hot blood. At the same time it has not affected the nutrition of the living cells within. This is the first step to cooling attempt. Compression and movements within a closed space like joint would invariably create more heat in the blood- fed cartilage of the joint. Further step to cooling is the presence of a jelly-like viscous fluid which lubricates the joint surfaces. Still another point is the stratified structure of the cartilage. Joint-cartilage has many layers of fibers and micro-tunnels which allow micro-circulation of the fluids due to compression and decompression of the cartilaginous surface. This type of circulation has the cooling effect similar to sweating on the surface of an earthen pitcher.

This anatomical and bio-mechanical situation can be captured in mathematical modeling taking all other parameters like bone strength, efficiency of ligaments, muscles and nerves within normal limits. The perpendicular and tangential lamellae of the bone at the concerned area, the location of the weight bearing surface (WBS) and the centre of rotation (CR) has been shown in the accompanying [Figures.1 & 2] where CR is shown in arrow head and WBS in a line.

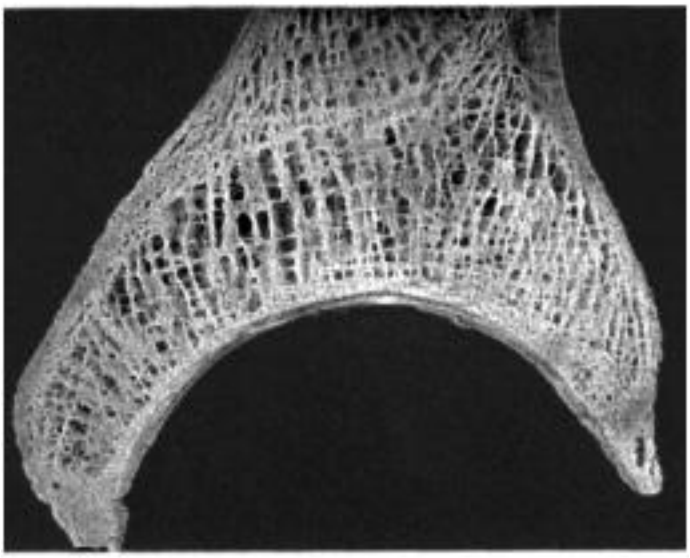

Figure 1: Perpendicular & tangential lamellae of bone at acetabulum i.e. at weight transmitting surface

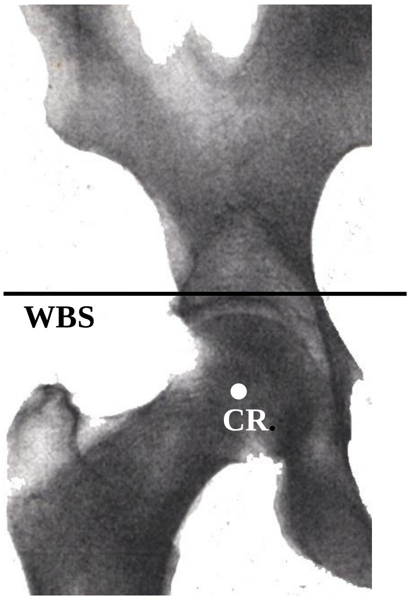

Figure 2: Showing Centre of rotation and weight bearing surface by straight line.

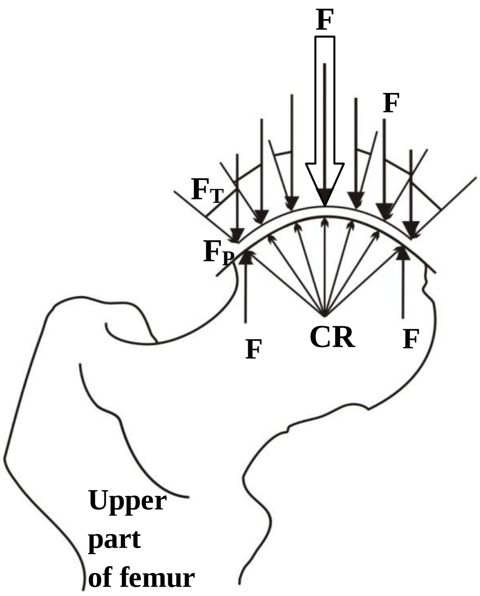

Figure 3: Force, due to body-weight coming over surface of the acetabulum is transmitting towards the center of rotation of femur and the reaction force

We will now consider transmission of forces through the head of the femur. Vertical forces on the WBS are resolved into tangential F_T and perpendicular F_P forces. As shown in the accompanying Fig.3.

The F_T forces will neutralize each other by acting in opposite direction while the clear F_P will terminate at the CR.

There is some force absorbing structures in this joint. The acetabular cavity is *homœoid or focaloid* as because it allows enough free spaces with spherical femoral head to keep incongruence for maintaining lower friction of free movements.

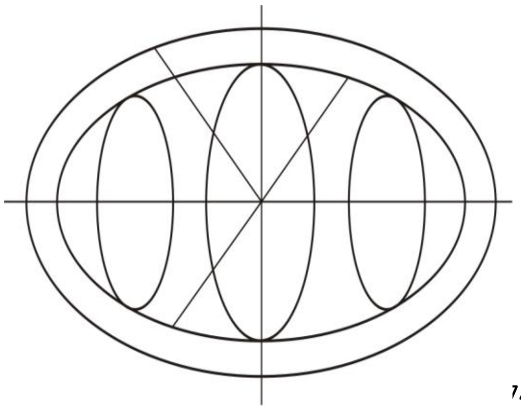

Figure 4A: Homœoid

Homœoid (Fig.4A) is a shell bounded by two similar ellipsoids having a constant ratio of axes. Given a chord passing through a homœoid, the distance between inner and outer intersections is equal on both sides.

A focaloid (Fig.4B) is a shell bounded by two concentric, confocal ellipses in two-dimension or ellipsoids in three-dimension whose plane sections are ellipses.

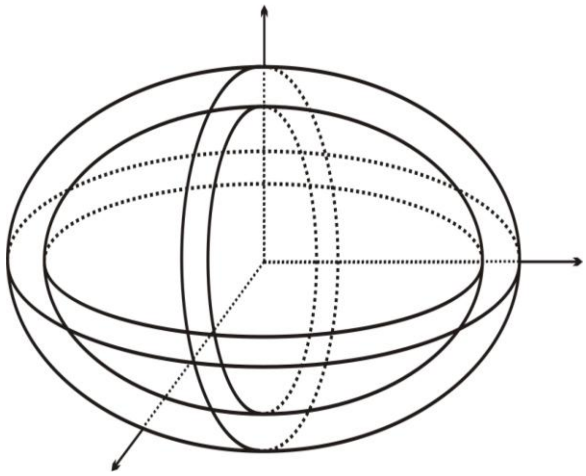

Figure 4B: Focaloid

The femoral head absorbs forces through the shortest path like *helicoid* or *conoid.* Patterns are shown in the accompanying figures 5A & 5B.

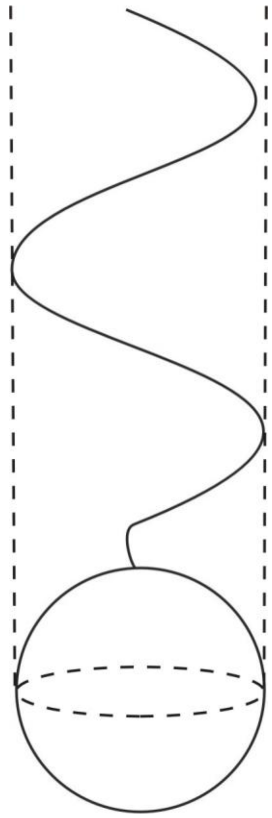

Figure 5A: Helicoid i.e. Circular or cylindrical helix

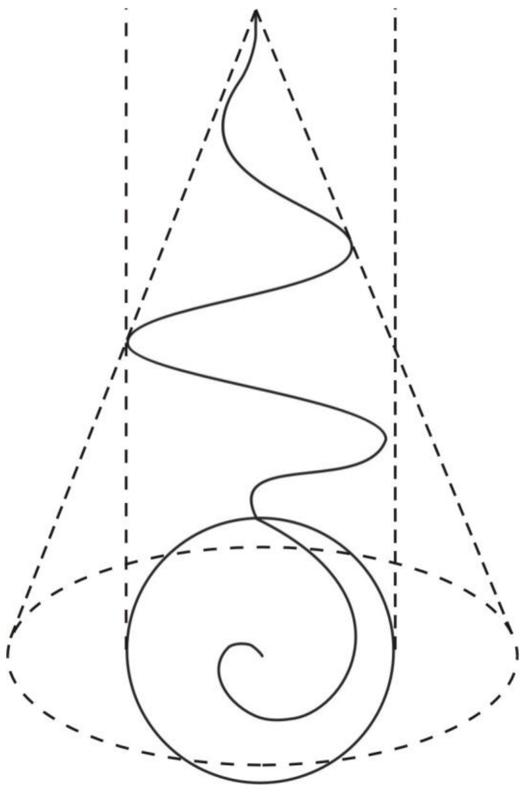

Figure.5B: Conoid i.e. Conical helix formed by equiangular spiral

The helicoid (Fig.5A) is the minimal surface having circular helix as its boundary. Its parametric form of equation is $x = u \cos v$, $y = u \sin v$, $z = cv$ which has obvious generalization as elliptical helicoids. Considering $z = - cv$ it gives cone. The helicoids can continuously deformed into catenoid by transformation: $x(u, v) = \cos\alpha \sinh v \sin u + \sin\alpha \cosh v \cos u$, $y(u, v) = - \cos\alpha \sinh v \cos u + \sin\alpha \cosh v \sin u$, $z(u, v) = u \cos\alpha + v \sin\alpha$ where $\alpha = 0$ corresponds to helicoids and $\alpha = \frac{\pi}{2}$ to a catenoid.

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Conoid (Fig.5B) is a geometric surface formed by rotating parabola, ellipse and hyperbola. It is a Catalan surface with all of its rulings intersects on a fixed line. For example, the hyperbolic paraboloid i.e. $z = xy$ is a conoid (right conoid) with x-axis and y-axis as two axes. General parametric equation is: $x = v \cos u + lf(u)$, $y = v \sin u + mf(u)$, $z = nf(u)$ where $\{l, m, n\}$ is a vector parallel to the axis of the conoid and f(u) is some function. Now for $l = m = n = 0$ give a right conoid.

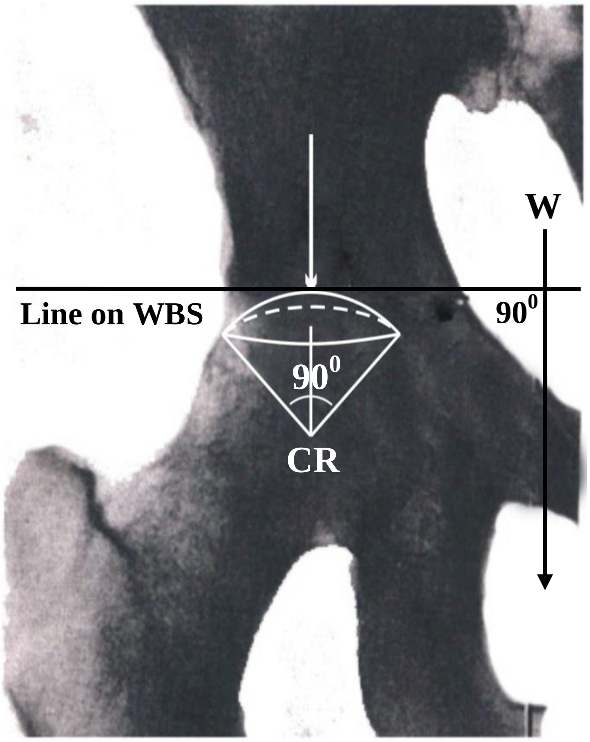

Figure.6: WBS makes a contact area with head of femur which makes inverted cone subtending 90^0 at the CR

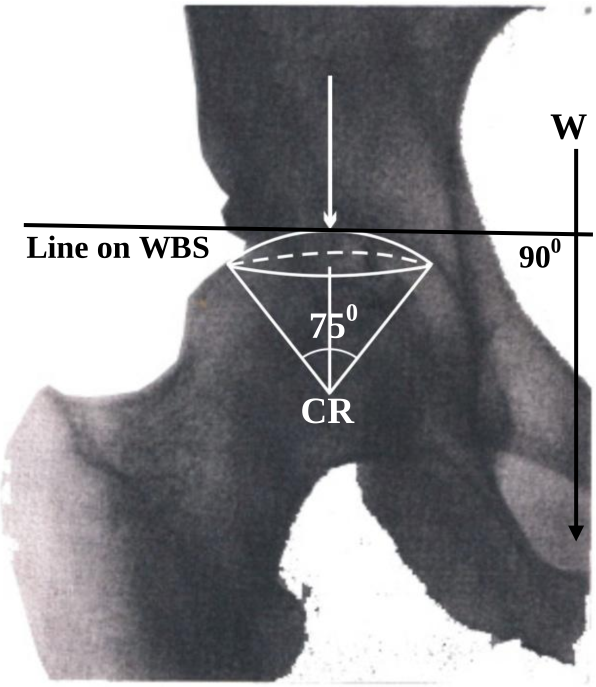

Figure.7: WBS makes a contact area with head of femur which makes inverted cone subtending 75^0 at the CR.

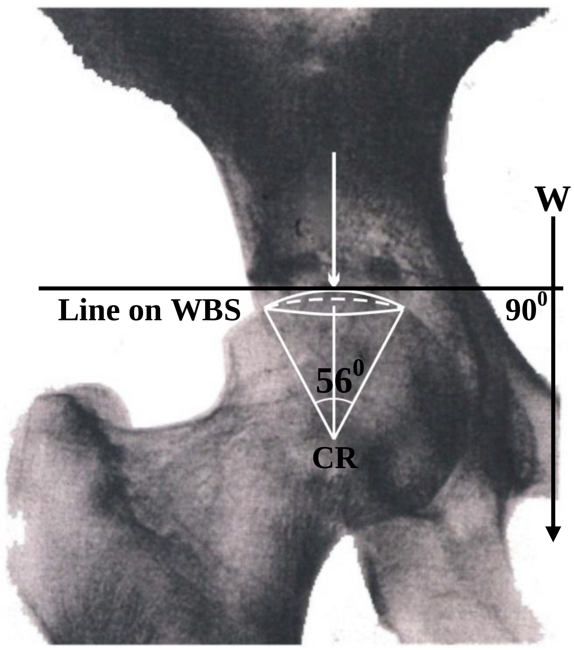

Figure 8: WBS makes a contact area with head of femur which makes inverted cone subtending 56^0 at the CR

Body weight transmission through the hip can vary with the anatomical variations. The accompanying figures (Figures nos.6, 7, 8) will clarify the matter forming inverted cones with spherical base upward (Fig.9A). The area of bases determines the contact area between inner surface of the acetabulum and head of the femur. We also see that the perpendicular forces on the WBS form a cone whose semi-vertical angles vary from individual to individual but line of body-weight transmission always keeps 90^0 with line of WBS where lines of WBS are horizontal.

The intensity of force transmission increases as the semi-vertical angles decrease:

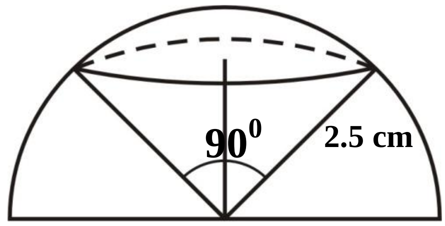

Figure.9A: Base of the cone is a part of the surface of a sphere.

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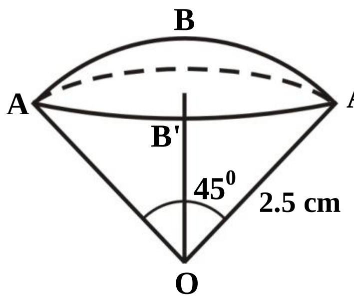

Figure.9B: Cone (OABA'O) forms about CR (O) having semi-vertical angle 45^0

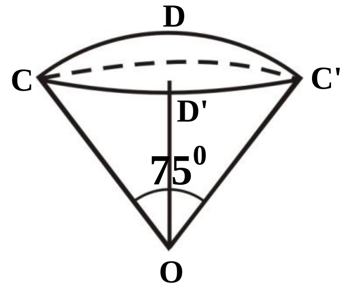

Figure.10: Cone (OCDC'O) forms about CR (O) having semi-vertical angle 37.5^0

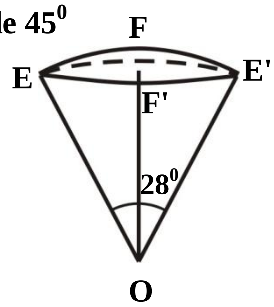

Figure 11: Cone (OEFE'O) forms about CR (O) having semi-vertical angle 28^0

Area of surface OABA'O = 22.92 cm^2 where force / body-weight (W) per unit area = 0.044W Kg (Fig.9B). Area of surface OCDC'O = 16.32 cm^2 where force / body-weight (W) per unit area = 0.061W Kg (Fig.10). Area of surface OEFE'O = 9.41 cm^2 where force / body-weight (W) per unit area = 0.106W Kg (Fig.11) [Ref.7].

Next we would like to consider how the shape and the angulations between the head, neck and the frontal plane determine the speed of the movement. Figure 12 showing the diameter of head and the accompanying x-ray image (Fig.13) shows that the head is occupying more than $\frac{2}{3}$rd of the sphere.

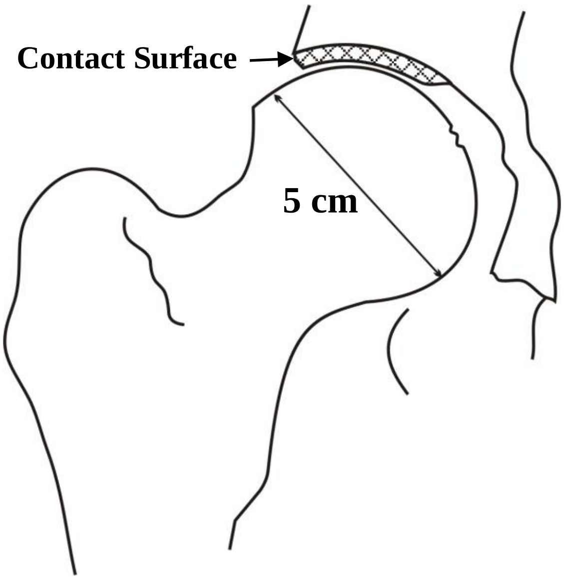

Figure 12: Showing diameter of nearly spherical head of femur and contact surface

Figure 13: Showing the picture of head of femur nearly two-third of a sphere

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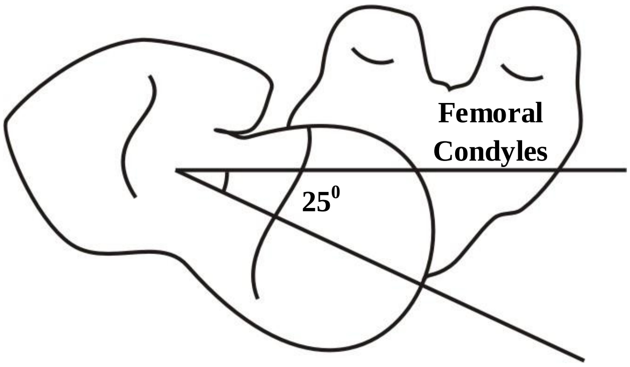

Figure 15: Presenting angular turning of femoral neck with condyles from the top of the frontal plane.

Within average people angle between the neck and the shaft is 125^0 (Fig.14) and the angle between the neck and frontal plane is 25^0 (Fig.15) and it is the normal phenomena. The x-ray plates show small and high slung pelvis with a slender shaft.

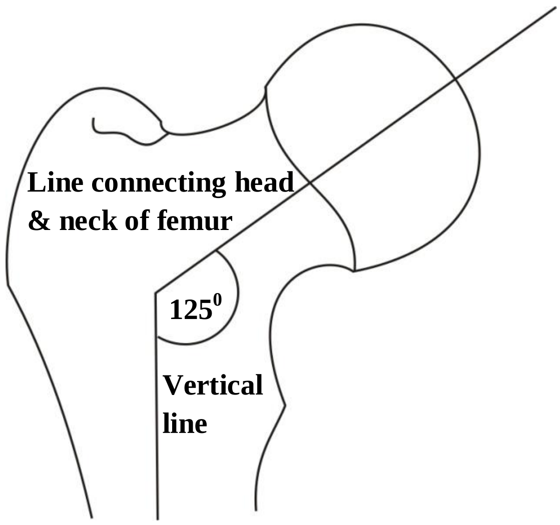

Figure 14: Showing angular presentation between shaft and neck of femur along frontal plane

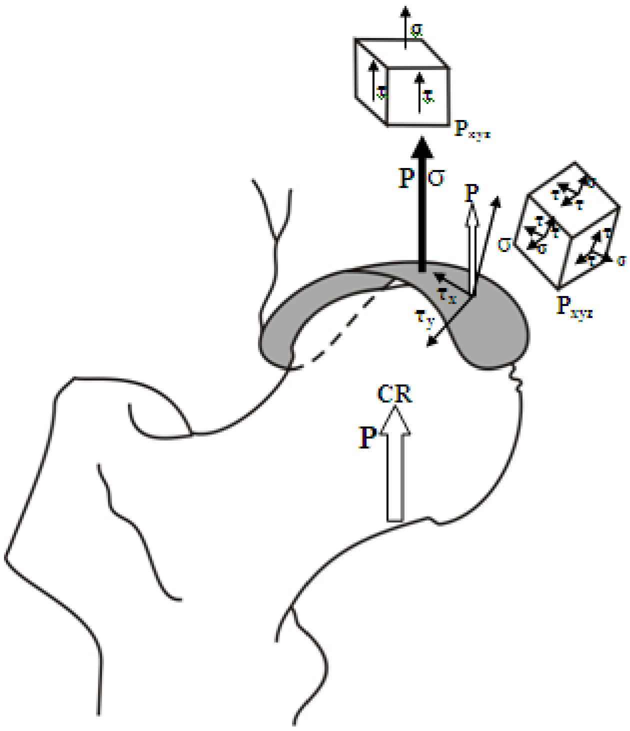

Figure 17: Showing reaction force (P), resolution of forces on WBS

Figure 16: X-ray of Hip

Resolution of forces on the WBS is shown in Fig. Resolution occurs in three mutually perpendicular directions i.e. σ, τ_x and τ_y, where P is the force in vertical direction, τ_x and τ_y are mutually perpendicular on the WBS. In such cases the maximum force P will be exerted at the CR of WBS, where as τ_x and τ_y will neutralize each other acting in opposite direction due to uniformity of the curvature of WBS i.e. from symmetrical surfaces on either sides of the force P. Right hand cube is showing the resolution of forces σ, τ, τ in three mutual perpendicular directions. Top cube is showing that components are perpendicular all over. It has also been mentioned in the figure that WBS keeps horizontal and symmetrical. P is the reaction force at CR (Fig.17).

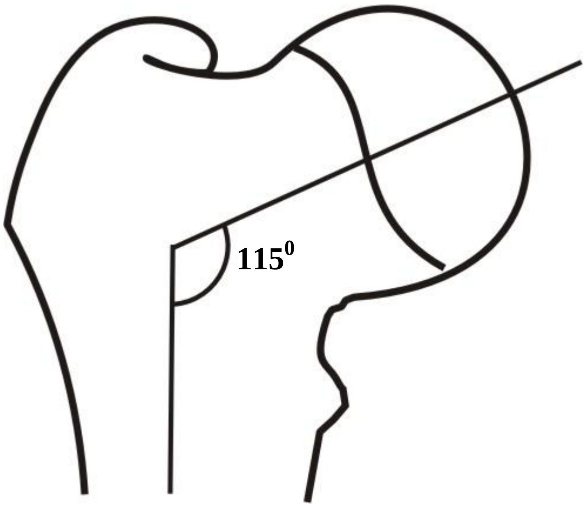

Figure 18: Showing compact angular presentation between shaft and neck of femur along frontal plane

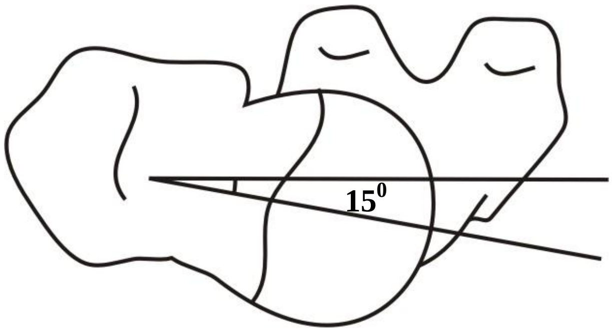

Figure 19: Presenting lesser angular turning of femoral neck with condyles from the top of the frontal plane.

Figure 20: X-ray of compact Hip

Take another example where head of femur just exceeds a hemisphere and the angles are 115^0 (Fig.18) and 15^0 (Figs.19). The shaft is thick, pelvis large and broad which is accompanied by x-ray images (Fig.20).

Forces at the joint articular surface vary from zero to more than 10-times of the body-weight (Andriacchi et al, 1997 & Paul., 1976; Ref.8). Similarly contact areas also vary in complex manner. It has been estimated that peak contact stress may be upto 20 MPa at the hip while rising from chair and upto 10 MPa during stair climbing (Hodge et al., 1986). Thus under physiological loading condition articular cartilage is a highly stressed material.

Now we will consider the cartilaginous layer. Fig.21 shows the different histological layers in the cushion pad of the cartilage in the joint. The layers are arranged as follows from the articular surface to the bone surface. i) superficial tangential layer (7%), ii) transitional zone 20%, iii) Middle zone of radiate zone 53% whereas this zone capable of absorbing compression and reinstate after release iv) deep layer 20% separated by tide mark which is a layer of calcified cartilage with lower flexibility but of hardness, then the layer of v) subchondral bone and cancellous bone. The upper three layers are capable of absorbing tensile as well as compressive forces. Cartilage has the mechanical efficiency of modifying the thrust by increasing the surface area of load distribution and thus providing resistance to wear and tear at the weight bearing surface. Thereafter, it reinstates normalcy by the spring effect. It also minimizes the frictional forces arising out of movements due to flow of interstitial fluid through the porous permeable solid matrix.

Mathematical expression of force absorbing capacity may be given as (Fig.22): $T = \frac{\mu.L.N}{d}$ where = Tensile stress of cartilage surface; L = Length of the joint-structure or cartilage; N = Vertical Stress on cartilage; μ = Dynamic frictional co-efficient; d = Thickness of the upper layer of cartilage.

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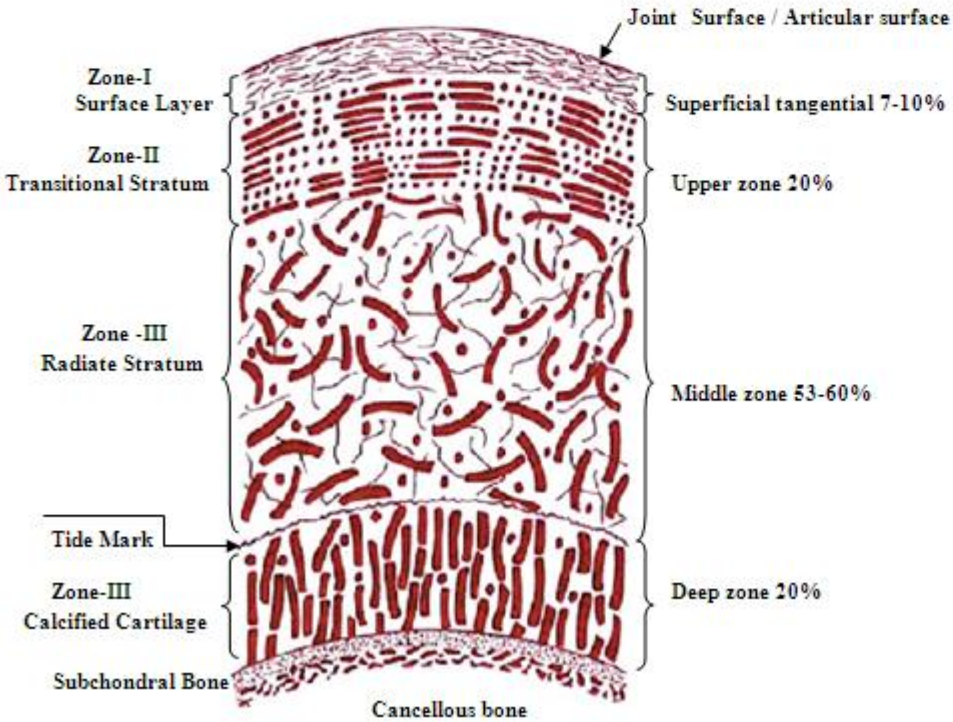

Figure 21: Structure and layers of articular cartilage

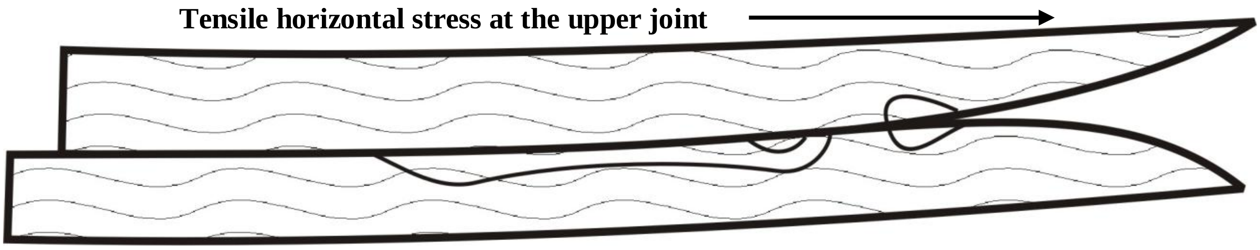

Figure 22: Distribution of horizontal tensile stress along articular cartilage in joint during motion

The porosity of fluid is determined by $\alpha = \frac{V_E}{V_T}$ where V_E = Effective flow of fluid through pores and V_T = Total fluid within the cartilage. Therefore porosity is a geometric concept and is in geometric progression. Articular cartilage is of high porosity nearly 0.8 i.e. of 80%. Here pores are interconnected and therefore permeable. Permeability can easily be measured by the volume of flow of fluid through porous permeable material. Here $p \propto \frac{1}{F}$ where p = Permeability and F = Frictional drag force exerted by the fluid flowing through the porous material. Thus it measures that $R \propto S$ where R = Resistive force and S = Speed of the fluid flowing through the porous permeable material. This frictional resistive force is generated due interaction of the interstitial fluid and the pore walls. Now, Permeability co-efficient = $p = \frac{A}{F}$ where F = Frictional drag co-efficient and A = Area through which fluid is flowing. But articular cartilage has very low permeability. So, it generates very high frictional resistive forces when fluid is compelled to flow through porous solid matrix.

Fluid flow through articular cartilage induced by solid matrix compression is an indirect method of determining the permeability of the tissue. The Permeability co-efficient = p = $\frac{Q.d}{A(P_1 - P_2)}$ where Q = Quantity of fluid flowing per unit time; d = Thickness of the cartilage; A = Cross sectional area of cartilage; P_1 = Initial pressure of fluid on compression; P_2 = Pressure of fluid after permeation.

This interstitial fluid pressurization determines the load bearing and lubrication capacity of tissue. This is a remarkable phenomenon in the sports activity. Thus force absorbing capacity of the joint cartilage can be deduced mathematically.

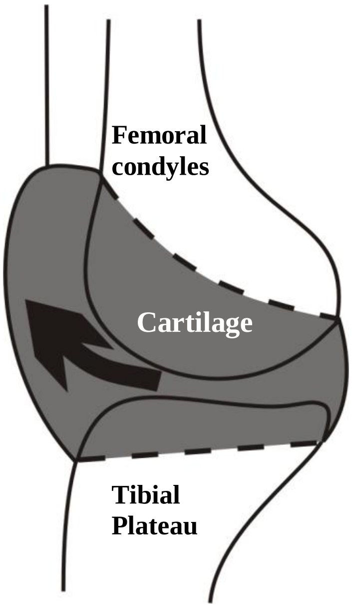

Figure 23(a): Flow of cartilage in extension

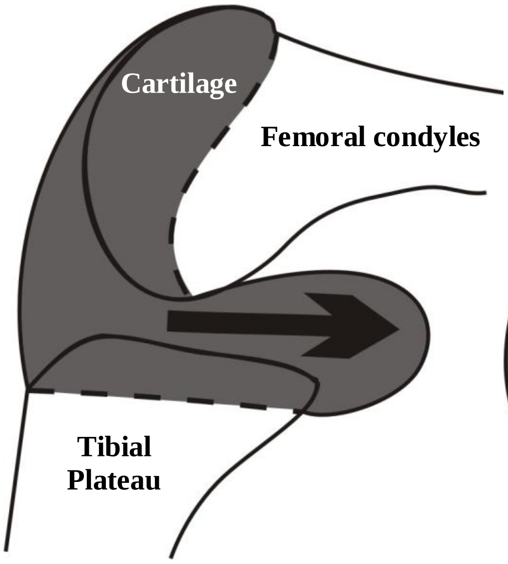

Figure 23(b): Flow of cartilage in flexion

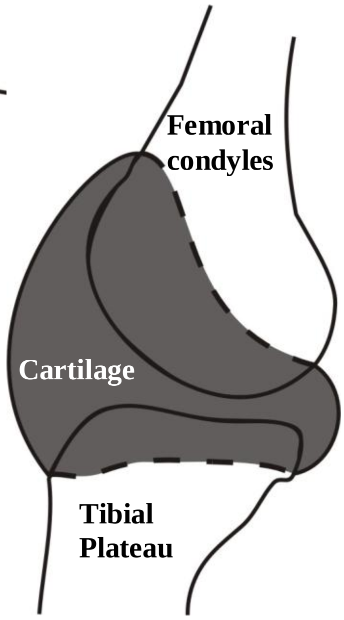

Figure 23(c): Existence of cartilage in semi-flexion

Now we can consider the movement of the fluid within the joint. Fig.23(a), (b) & (c) show the position of fluid in the knee joint during various postures i.e. extension, flexion and semi flexion. The viscosity and elasticity of the joint fluid plays an important role during sports.

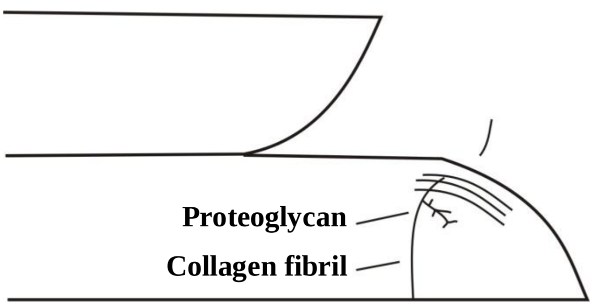

Figure 24(a): Flow of cartilaginous fluid before joint compression

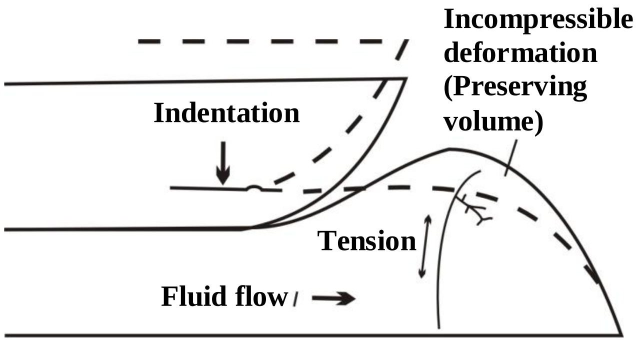

Figure 24(b): Flow of cartilaginous fluid after joint compression

Fig. 24(a) & 24(b) give a diagrammatic representation of the relative positions of fluid and cartilage during movement. The flow of fluid within the joint depends on visco-elasticity. Now, $F_{MT} \propto P_E$ where F_{MT} = Flow of fluid through the micro tunnel and P_E = Exerted pressure.

Compression of joint gives an exothermic effect where as expansion turns it to an endothermic state. This alternation of expansion and compression within the joint keeps it reasonably cool even during the height of activity. This dissipation of heat can be shown in the mathematical model as $C_S \propto H_E$ or, $C_S = F.H_E$ where C_S = Compressive strain = physical which tends to structural compaction, H_E = Evolved heat and F = constant depending body-weight.

Shock absorption: Presence of proteoglycan within the cartilage acts like a shock absorber sponge. We can express the matter mathematically. $\rho = \frac{\beta^2}{\kappa}$ where ρ = Apparent permeability; κ = Coefficient of expansion; β = Resolution coefficient.

We can consider these simple clues in the weight bearing joints along with other details already known to the trainers and plan for the appropriate sports activity of the trainee.

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