On Ligaments and Movements

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Ligaments are the connective tissue that binds bone to bone. They are, for most purposes, inextensible, which is as it should be. Loose ligaments allow excessive play in a joint and if ligaments were extensible they would eventually become too loose to maintain a stable joint. It is their inextensibility that is crucial to their role, which is generally to restrict joint motion in particular directions and to specific ranges of motion.

Having said that, it is necessary to backtrack a bit and admit that there is a small amount of extensibility in actual ligaments. For most it is on the order of 5% increase in length, but this is usually only with a sustained tension upon the ligament. This stiffness is because of the stiffness of the collagen fibers that form a major component of ligaments. This small amount to extensibility allows for some joint play. It also allows enough movement to free what would normally be a locked joint. Most joints have cartilage, which is much more deformable, therefore more important in small joint displacements near close-packed positions.

Any movement that tends to separate the ends of a ligament will eventually be restricted when the ligament becomes taut. At that point the two bones can move only in ways that will not further lengthen the ligament, which is in a circular arc about the fixed end of the ligament. The available endrange movements form a section of a sphere that has its center at the fixed attachment. Different parts of a complex ligament may have different movement surfaces. It is only where these movement surfaces intersect that movement is permitted. This is the central premise of all that follows.

The spatial structure of a ligament and its relations to its bones will determine how one bone moves relative to the other. There are certain symmetry conditions where one may effectively shift movement surfaces so that they have a common origin (see circular ligaments, below). There are also configurations that do not allow such shifts and thus place restrictions upon the permitted movements. The restriction of bone movements by ligaments is the problem that is addressed here.

The Filament-Ligature Model

To differentiate between anatomical ligaments and the theoretical construct that we will be using to model ligament actions, let the latter be called a ligature. If we call an element of a ligature a *filament*, then a taut straight filament may be modeled by a framed vector, $\boldsymbol{\lambda}$. The length of the extension vector is the length of the filament within the ligament and its direction is aligned with the filament. The location vector is the location of the fixed end. The frame of reference is the twist in the filament. The orientation is partially the relationships between the filaments.

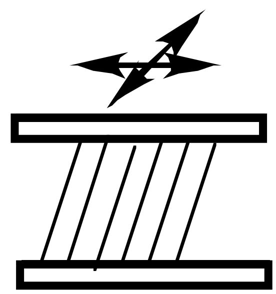
There are filaments that are not straight. Helical ligaments, for instance, which will be considered below. For non-linear filaments, the filament must be represented by an array of points or framed vectors.

A *ligature* is array of filaments that are fixed at one end and free to move at the other end, but bound to bone at each end. In some ligatures, the filaments will form a regular parallel array; in some ligatures, they are interdigitated, so that some filaments run in one direction and others in other directions. In many ligatures the filaments are straight, but in some they are helical. It is by tracing the changes in the filaments with movement that we hope to come to an understanding of the function of different types of ligatures.

The set of rotation quaternions that move $\boldsymbol{\lambda}$ is any unit quaternion with a unit vector. In many situations, the axis of rotation takes its origin from the fixed end of the filament, but there are also situations where the axis of rotation is not through the filament. The permitted rotations for taut ligatures are rotations that transform an array of points in the distal end of the ligature while maintaining the lengths of the filaments the same or shorter and the same distances between the points in the distal array. In other words, the only transformations that are allowed are those that cause rigid transformations of the end arrays of the ligature. This derives from the fact that ligaments are attached to bone at both ends. If a ligature is not taut, then the lengths of its filaments must be less than their taut lengths. Movements that make some ligatures longer than their taut length are forbidden.

Flat Planar Ligaments

The first shape that we will consider is the ligament that stretches as a sheet from one bone to another. When the ligament is taut the moving bone can only move in directions perpendicular to the length of the ligament. If we arrange the joint so the fixed bone is inferior and the moving bone is superior with the ligament extending directly between them, then the allowed movements are swings in arcs about the attachment of the ligament to the fixed bone.



Planar

This applies to the attachment site on the bone, but remember that a bone may be able to swivel about its ligamentous attachment sites. With a single ligament the ligament may be taut and yet the bones may move to open or close the joint that is bridged by the ligament. This allows a considerable amount of movement, but there are usually a number of other constraints. A swinging movement brings the bones closer together if they lie in the direction of the swing. If the bones are large, then there is very little movement in the directions towards the bones. Moving in the opposite direction will tend to separate the bones as they rotate about the fixed attachment. However, if there is another ligament on the opposite side of the joint, then that direction of movement will be compressing the joint for that ligament. That only leaves movement orthogonal to the bony side of the ligament. Often that is also blocked if the bones extend anterior or posterior to the ligament. This occurs for end-range extension of the knee.

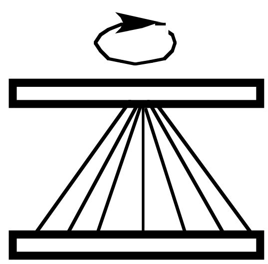
The way that the knee solves this problem for flexion is to have a rounded surface that allows the space between the tibia and femur to increase as the knee is flexed. As the knee is flexed, there begins to be lateral play in the joint, as one would expect. The knee is less stable, but one normally is not weight-bearing when the knee is bent.

In a flat planar ligature, the axes of rotation are located within a plane perpendicular to the ligature that includes the attachment site. This means that the allowed movements are ones that can be generated by rotating about the line of attachment and then shifting the distal end of the array in the new plane of the ligature. The order of the movements may be reversed.

A rotation changes the direction and orientation of the filaments in a ligature, but not the internal relationships between the filaments. A shift changes the internal relationships between the filaments, that is, it produces a strain. In effect, it produces an internal rotation.

Conical and Triangular Ligaments

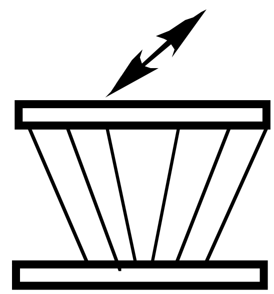
In a conical or triangular ligament there is a broad base of attachment and a narrow attachment. This arrangement tend to restrict lateral or anterior/posterior movements, because they tend to stretch fibers on the side of the ligament that is opposite the direction of movement. There are two types of movement do not stretch these ligaments as much. Rotation about the narrow attachment site will not strain the ligament as much. These can be about axes of rotation in the plane perpendicular to the long axis of the ligament, about an axis along the length of the ligament, or any vector sum of those vectors. The principal constraint is that the axis of rotation pass through the apex of the ligament.



Conical

Wedge Ligaments

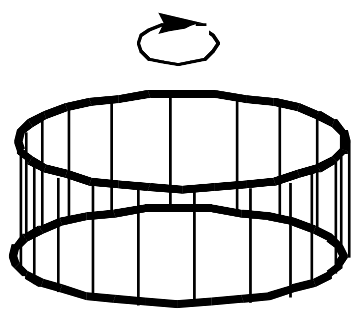
In the extreme, these might be inverted triangular ligaments. However, a wedge is a ligament that diverges as it moves towards the moving bone. The fixed attachment is broad, but not as broad as the moving attachment. The critical feature is that movement in the plane of the ligament is always going to lengthen a part of the ligament and force that end down, but forcing the leading edge down stretches the trailing edge. Rotation about a vertical axis stretches both ends, therefore the direction free to movement is movement perpendicular to the plane of the ligament. The moving bone moves perpendicular to the plane of the ligament and closer to the fixed bone, unless it is able to tilt.



Wedge

Circular Ligaments

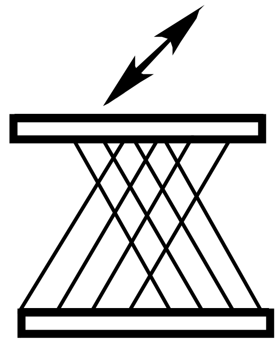
A special case of a sheet ligament is the circular ligament, in which the fibers form a ring. It is possible for the rings to shift horizontally relative to each other. If the fibers are vertical then all fibers are stretched the same so the moving ring moves horizontally and towards the fixed ring. Another movement that is permitted is the twisting of the moving ring about a vertical axis of rotation centered in the ring. This also draws the moving ring towards the fixed ring.



Circular

Crosshatch Ligaments

These ligaments can take a number of forms. The conical or triangular ligament may be a form of crosshatch, but the more general form is the overlapping of sheets of fibers that are at an able to each other. Since the fibers are oriented in different directions the movement surfaces for the different sets of fibers are angles to each other and the only permitted movements are the ones that lie along the intersection of the surfaces or close to those lines. This means that they are uniaxial, with the axis aligned with the plane of the ligament.



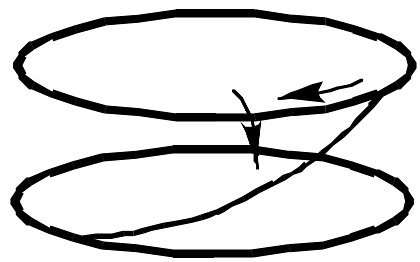
Cross Hatch

Helical Ligaments

First we consider a single fiber. As the fiber passes between the bones it also travels circumferentially. If all the fibers travel in the same direction, then this is just a version of the circular ligament in which the moving bone is twisted relative to the fixed bone. It can move the same ways: tilting and rotating about a central vertical axis. It will much further in the direction that rotates the moving bone towards the fixed attachment.

There is an interesting property of circular ligaments that can be seen if we allow the fibers to become very long. If we allow the moving bone to rotate 180° about a vertical axis then all the fibers intersect in the center of the joint space, forming two cones that meet at their apices. If we allow less rotation then the fibers form a hyperboloid surface. The point is that the fibers tend to squish the center of the joint space and pull the bones together. If we place an incompressible matrix in the center of the ring, between the bones, then the fibers can not squeeze centrally and the bones can not come together. This greatly restricts the amount of movement that is possible. On the other hand, the matrix will act as cushion between the bones that is allowed deform by pressing peripherally. However, the circular ligament restrains lateral movement by pulling the bones together until the peripheral distortion strains the ligaments. The ligament is resisting compression by being strained by tension along its length.

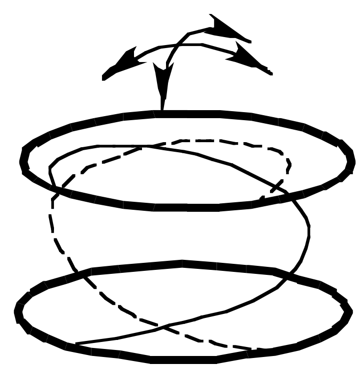
If all the fibers in the ring went the same direction in a helical manner then compression would cause the moving bone to rotate relative to the fixed bone so that the fibers could become more vertical.



Helical Ligament

Crossed Helical Ligaments

Uni-directional helical ligaments are not normally found in bodies, but crossed helical ligaments are common. In crossed helical ligaments there are fibers the arc in both directions, usually in alternating layers. Since there are contrary fibers rotation about a central vertical axis will lengthen one set and shorten the other set. This is possible if there is no barrier to the lengthening fibers shifting centrally, but there is usually a central matrix that is deformable, but incompressible. This arrangement allows a small amount of rotation before the central matrix is compressed by the approximating bones and the centrally converging fibers.



Crossed Helical

The movement that is allowed to the moving bone is to tilt. This is because tilt is roughly perpendicular to the helical fibers. It is usually at an angle of about 60°, but since the fibers are much longer they can be displaced further without undue stretching. The details are complex and require a computer model to carry out the calculations. This has been done elsewhere (***Strains in Intervertebral Discs***).