Figure 3.1 illustrates the geometric relationships between the LFT (Marker#29), APT (Marker#31), SH (Marker#22), RFT (Marker#24), and PPT (Marker#33) for diastole (left panel) and systole (right panel).

Figures 3.3a and 3.3b plot, for hearts H1-H6, the distance between the APM tip and the fibrous annulus from the LFT to the SH (D2931, D1531, D3031, D2231), the distance between the PPM tip and the fibrous annulus from the RFT to the SH (D2433, D2133, D2333, D2233), the distance between the papillary tips (D3133), LVP, and identify the time of mitral valve opening (MVO) and closing (MVC).

Note, in Figures 3.3a and 3.3b, that the distances from the APT to the fibrous annulus (D2931, D1531, D3031, and D2231) and the distances from the PPT to the fibrous annulus (D2433, D2133, D2333, D2233) are relatively constant throughout the cardiac cycle, in spite of the wide variation in the distance between the papillary tips (D3133, greatest at end diastole, decreasing during ejection, then increasing during filling).

Table 3.1 quantifies the changes in all these distances throughout the cardiac cycle. The data in this table were obtained by first analyzing 130 consecutive samples for the 3 beats in each individual heart, finding the maximum and minimum values for this dataset in that heart, then computing the percent change for that heart as 100*(max-min)/min. The Maximum change observed for the 6 hearts analyzed is shown as MAX%, the minimum change observed as MIN%, and the mean change for the 6 hearts is MEAN%. As can be seen, even with these very stringent criteria, changes in the distances from the papillary tips to their respective half of...
the fibrous annulus were small, ranging from 2-7%, while the distance between the papillary tips (D3133) ranged from 32-60%.

These nearly constant papillary tip to fibrous annulus distances suggest rather tight coupling between the papillary tips and the fibrous annulus. The material basis for this coupling can be observed anatomically (Figures 3.2a, 3.2b, and 3.2c) as relatively thick, so-called “strut” chordae, emanating from the papillary tips, inserting into the belly of the anterior leaflet, continuing on as somewhat diffuse structures on the ventricular side of the anterior leaflet to insert with the leaflet into the fibrous annulus and chordae from the papillary tips to the trigones. The differences between Figure 3.2a and 3.3b suggest anatomical differences between ovine and human chordae, although both species have chords from the papillary tips to the anterior leaflet belly and from the papillary tips to the trigones that could result in this constant-distance behavior.
Such relatively constant distances between the papillary tips and the fibrous annulus have potentially important implications. If, to a crude first approximation, we model the fibrous annulus-APT and -PPT connections as chordal threads, capable of supporting tension, but buckling in compression, then the only way to maintain these constant distances is to rotate the papillary tips around axes defined on the fibrous annulus. We define two such axes for each heart in Figures 3.4a, b, and c.

- The first axis, for the APT (#31), has its origin at the SH (#22) and extends through the LFT (#29). A plane 22-29-1 (blue) anchors this axis to the LV apex (#1). Another plane 22-29-31 (red) contains the chordal threads to the APT (#31).
- The second axis, for the PPT (#33), has its origin at the SH (#22) and extends through the RFT (#24). A plane 22-24-1 (green) anchors this axis to the LV apex (#1). Another plane 22-24-33 (red) contains the chordal threads to the PPT (#33).

We further define:

- “pat” as the projection of the APT (#31) on the 22-29-1 plane and “qa” is the point on the 22-29 axis where a normal to this axis passes through the APT (#31).
- $\alpha_{31}$ as the 29-22-pat angle in the 22-29-1 plane.
- $\beta_{31}$ as the APT angle 31-qa-pat with respect to the 22-29-1 plane, with positive angles toward the lateral annular marker (#18).
- LAC31 as the #22 to qa distance.
- RAC31 as the #qa to APT(#31) distance
- “ppt” as the projection of the PPT (#33) on the 22-24-1 plane and “qp” is the point on the 22-24 axis where a normal to this axis passes through the PPT (#33).
- $\alpha_{33}$ as the 24-22-ppt angle in the 22-24-1 plane.
- $\beta_{33}$ is the PPT angle 33-qp-ppt with respect to the 22-24-1 plane, with positive angles toward the lateral annular marker (#18).
- LPC33 as the #22 to qp distance.
- RPC33 as the #qp to PPT(#33) distance

Note that LAC31, RAC31, and $\beta_{31}$ describe the APT (#31) in a cylindrical coordinate system (defined by 22-29-1), and LPC33, RPC33, and $\beta_{33}$ describe the PPT (#33) in another cylindrical coordinate system (defined by 22-24-1).

An important finding demonstrated in Figures 3.5a and 3.5b is that RAC31 and RPC33, the radial components of their respective cylindrical coordinate systems, are nearly constant. This indicates that the two coordinate systems just constructed (using 22-29-1 and 22-24-1) provide axes of symmetry around which the papillary tips exhibit almost pure rotation. This tends to justify our chordal thread assumption used to derive these coordinate systems. Further, whether or not this assumption is valid, these coordinate systems reduce the very complex papillary tip dynamics in 3D space to simple rotations around anatomically definable LV axes. This is important to allow us to gain a greater understanding of the role of these papillary muscles with respect to the mitral valve within the LV chamber.
We next explore some of the implications of the data in Figures 3.5a and 3.5b, observing that:

- Papillary tip motions can be almost completely characterized as a rotation around their respective trigone axes ($\beta_{31}$ around 22-29 and $\beta_{33}$ around 22-24, both plotted in red). This rotation follows LV flow (actually, more properly, EDV), not pressure, becoming increasingly positive during LV filling and increasingly negative during LV ejection.
- The rotation of the papillary tips ($\beta_{31}$, $\beta_{33}$) is least at mitral valve opening (MVO), but always $> -7^\circ$ (i.e., very near the fibrous annular -LV planes), increases rapidly during diastolic filling to $\geq 0^\circ$ during diastole, and is always positive at mitral valve closure (MVC). This is important and will be discussed in subsequent chapters, but for now we only point out that large, negative $\beta$’s would place the papillary tips into LV outflow tract territory.

- Because papillary tip motions can be almost completely characterized as a rotation around their respective trigone axes, and their chordal distances to the fibrous annulus vary so little (without buckling), this implies that the strut chords are always in tension and that this tensile force is exerted:
  - by the anterior papillary muscle in the APT-LFT-SH plane (shown in red in Figures 3.4a, b, and c), directed in the narrow range between the force vectors labeled as F1 and F2 in Figures 3.4a, b, and c, and
  - by the posterior papillary muscle in the PPT-RFT-SH plane (shown in red in Figures 3.4a, b, and c) and directed in the narrow range between the force vectors labeled as F3 and F4 in Figures 3.4a, b, and c.

- We know something about this force. Salisbury, et al.\(^1\), implanted force transducers in series with canine strut chordae and showed that strut chordal force was always tensile throughout the cardiac cycle, with a maximum of 25-75 gm and a minimum during diastole of about 12 gm. Van Rijk-Zwikker et al.\(^2\) showed that strut chordae remain under tension throughout the cardiac cycle. Nielsen, et al.\(^3\), also implanted force transducers in series with ovine strut chordae and showed that maximum force was about 0.5-0.9 N ($\approx$50-90 gm), in agreement with Salisbury, et al.\(^1\). It is important to emphasize that these are very small forces, approximately an order of magnitude less than the force produced by systolic pressure on the surface of the anterior leaflet. So, at this point, we have a good estimate of the magnitude of strut-chordal force component and now have a fairly precise estimate of its vector orientation throughout the cardiac cycle, as well.

- Marker #3 is the closest LV marker to the anterior papillary tip marker (#31). Comparing D2203 in Figures 3.5a and 3.5b with D2231 in Figures 3.3a and 3.3b, note that the variation in distance (D2203) throughout the cardiac cycle from marker #3 to the SH (#22) is more than 4 times that of the variation in distance D2231 from the anterior papillary tip (#31). Likewise, Marker #9 is the closest LV marker to the posterior papillary tip marker (#33). Comparing D2209 in Figures 3.5a and 3.5b with D2233 in Figures 3.3a and 3.3b, note that the variation in distance (D2209) throughout the cardiac cycle from marker #9 to the SH (#22) is also more than 4 times that of the variation in distance D2233 from the anterior papillary tip (#33). This strongly suggests that the bodies of the papillary muscles must serve as springs with variable spring constants that couple the large movements of the LV myocardium relative to the SH (#22) to the almost invariant distances of the papillary tips (#31 and #33) from the SH. As the LV fills in diastole and the papillary tips rotate around their trigone hinges and thereby increase their inter-papillary tip distance (D3133, Figures 3.3a and 3.3b), these springs must stretch because D2203 and D2209 increase during filling, but D2231 and D2233 are constant. As the LV empties during systole, the springs must shorten because D2203 and D2209 are gradually shortening (and wall thickness is increasing, as well, throughout systole), but D2231 and D2233 remain constant.

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In summary, then, we can liken the papillary tips (#31 and #33) to the tips of chordal “wings” (the red triangles in Figures 3.4a, b, and c) flapping around their attachments to their individual trigonal axes (22-29 and 22-24), with a simple rotation toward the lateral mitral annulus (#18) during LV filling, and a simple rotation away from the lateral mitral annulus (#18) during LV ejection. Each wingtip is attached to a continuously stretched papillary spring anchored at one end in the LV wall and pulling to maintain tension in the strut chordae at the other, thereby maintaining the papillary tips at a constant distance from the central fibrous annulus saddlehorn (#22) as the LV myocardium stretches and contracts throughout the cardiac cycle. The criteria leading to these dynamics set rather stringent limits on the location of the papillary muscle tips within the LV chamber. This could have implications with regard to fetal heart development.

But what are these struts doing? Their weak tension, along with their orientation, just about precludes any role for these struts as important factors in generating LV pressure, reducing LV dimensions to aid ejection, or holding the anterior leaflet steady against high systolic pressures. We begin to address this question in the next chapter.

REFERENCES
Figure 3.3a Distance between the APM tip (#31) and the fibrous annulus from the LFT to the SH (D2931, D1531, D3031, D2231) (left panels), the PPM tip and the fibrous annulus from the RFT to the SH (D2433, D2133, D2333, D2233) (right panels), distance between the papillary tips (D3133), LVP, and the time of mitral valve opening (MVO) and closing (MVC) for hearts H1-H3.
Figure 3.3b Distance between the APM tip (#31) and the fibrous annulus from the LFT to the SH (D2931, D1531, D3031, D2231) (left panels), the PPM tip and the fibrous annulus from the RFT to the SH (D2433, D2133, D2333, D2233) (right panels), distance between the papillary tips (D3133), LVP, and the time of mitral valve opening (MVO) and closing (MVC) for hearts H4-H6.
Figure 3.4a. Two views of the papillary tip relationships to the fibrous annulus and LV for hearts H1 and H2.
Figure 3.4b. Two views of the papillary tip relationships to the fibrous annulus and LV for hearts H3 and H4.
Figure 3.4c. Two views of the papillary tip relationships to the fibrous annulus and LV for hearts H5 and H6.
Figure 3.5a. Trigone-LV-Pap coordinate system results for hearts H1-H3.
Figure 3.5b. Trigone-LV-Pap coordinate system results for hearts H1-H6.