# Final Thoughts on the Control of Placement in Anatomical Systems

## *The Role of Placement in Anatomical Movements*

We started by noting that anatomical movements are about location *and* orientation. The combination of location and orientation has been called placement. For the eye, gaze is equivalent to placement.

Much of this book has dealt with the properties of placement and anatomical movements that change placement. One must consider both location and orientation because they are distinctly different attributes of an anatomical object and they change in different ways with anatomical movements. The nervous system must deal with both, because, to not do so, is to fail in the tasks of everyday living, which is often lethal in a competitive world. The relevance of both location and orientation to survival makes both relevant to us as we consider anatomical movement.

Rotations that occur in a single plane about a single center of rotation may occur in any order without affecting the final placement. However, if rotations pass out of a plane, then there is a concurrent twisting of the moving object and the order of the rotations is critical to the final placement. Most anatomical movements are not confined to a single plane of rotation about a single axis of rotation, therefore, placement must be a consideration in their planning and execution. If we are to understand those movements, we must consider not only location, but also orientation. In addition, if we are to understand the neural control of movement, we must consider placement.

## *Description of Anatomical Movements and Their Control*

While the approach developed in this book uses highly abstract mathematics, it must be made quite clear from the beginning that it is very unlikely that the nervous system operates by explicitly performing such calculations. The abstract approach to description of anatomy and the calculation of consequent movements is a tool for examining the movements and determining what logical tasks must be performed by the nervous system. Often the descriptions and calculations show that the movements have a deep irreducible complexity and computational richness. Even the simplest movements may be surprisingly complex. That complexity tells us something of the problems that the nervous system must solve in order to perform the movements.

The mathematical analysis is directed at understanding the movement, but understanding the movements may tell us something of the processes that control the movement. The nervous system does not perform quaternion analysis to control placement, but it must implicitly solve the same problems. Once we understand the problem that must be solved then it is necessary to turn to anatomical and physiological methods to discover how the body solves the problem.

In the chapter on the eye we explored the nature of eye movements and discovered that a system that guarantees that the orientation of gaze during fixation is appropriate to the direction of gaze will also ensure that saccadic eye movements land the eye on the new target with the proper orientation. Put that way, it seems obvious that such should be the case, but our analysis of gaze shows that an obvious solution, moving directly from the initial target position to the final target position, will generally lead to an incorrectly oriented eye upon arrival. The mathematics helps to understand the movement and, in this case, it indicated a possible physiological solution,

*Model Systems*

In order to develop this approach, it is necessary to apply it in a number of actual anatomical structures. However, it is important to choose problems where the anatomy does not overwhelm the mathematics. To that end, a number of model systems have been explored. Those introduced in this book have been an eyeball in its orbit, the upper and lower cervical spine, and flows in gels submitted to simple compression/tension or shear. Many of these model systems have been simplified or intrinsically less systems where we could begin to develop an understanding without the considerable detail that is characteristic of most anatomical systems.

It is my hope that the eye movement system will point the way to exploring motor systems in that it is a bounded system with a limited number of well defined elements and definite purposes that may be expressed as a clear set of criteria. All of these features make it an excellent model system.

By contrast, the hand/arm movement system evokes patterned activity in dozens of muscles in the hand, forearm, arm, and shoulder girdle during the simplest reaching movement. The movements themselves are complex, involving movements in different directions in several joints with interdependent spatial relations between the actions of the different joints. A very simple treatment of a part of that system was considered in the last part of the chapter on spin and swing.

In addition to the muscles that move the bones, there are many muscles in the trunk and other extremities involved in establishing the foundation for such a movement. Even if we reduce our consideration of reaching to the actual movers, there are often not clear criteria for the movement and there is certainly not a unique solution to the execution of the movement. There are many ways that the final placement may be achieved. It is almost certain that such criteria do exist for the nervous system and there are certainly mechanical and neurological reasons for a particular execution of the movement that actually occurs, but we are seldom privy to that information. Part of the process during the neural planning of the movement must be the meshing of these possibilities and constraints to attain both a particular location and a particular orientation in a smooth coordinated fashion. At this time it is unlikely that we will be able to give a definitive solution to the problem. Analysis of the movement possibilities may give insight into what it is that we should be looking for in the nervous system.

Even if we were aware of all the constraints on a movement in a system as complex as reaching with a hand and could write down an adequate anatomical description of the system, the calculations for the movements would be horrendous. Therefore, let us start with simple systems and simple movements and gradually expand our explorations as our grasp of the concepts is increases and methods are developed for dealing with complex systems of anatomical description.

Clearly, much more detailed and complex analyses are possible. The examples in this book have been kept simple enough that they can be fairly readily followed. With a good computer and sufficient time and effort, one can address very complex anatomies. However, as models become more complex the numbers of possible variables grows to the point where one can spend years exploring all the possibilities. That is why the consideration of the lower cervical spine assumed a very similar anatomy and movements in all the elements.

*Neural Networks Control Movements*

When creating these types of models, it becomes rapidly apparent that most movements are complex. Even in a system in which the anatomy is simple, such as the eye movements, the movements are difficult to fully understand when one considers their full expression. And yet, the nervous system controls movement with considerable competence and in exquisite detail. It seems that in order to handle that task the nervous system builds internal models of the process to be controlled and by passing the current state of the system and the anticipated action through that model it creates a pattern of efferent activity that induces the desired and necessary actions in the physical plant of muscles and bones and occasionally other anatomical objects, such as an eyeball or a gland. These internal models are built in patterns of neural connections, which may be called neural networks. These networks are apparently built initially according to genetic/developmental programs, but they are subsequently modified and tuned by experience. Such adaptive or learning networks are able to accomplish the actual calculation and performance of the necessary movements by manipulating placement.

It is my personal intuition that as we study other systems we will find that a great deal of the computation is handled by neural networks that generate virtual surfaces subject to the particular constraints of the action and anatomical movement reflects movements in that logical surface. The gaze-muscle length surface for eye movements is an example of such a logic surface generated by a neural network. It seems that the problems that need to be solved on the fly during routine, everyday, anatomical movements are so computationally demanding that they can be accomplished only with such an adaptive system of anatomical connectivity within the nervous system. Examination of the controlled movements may suggest many interesting properties of the neural network, without actually exploring the physical plant of the movement system.

*The Role of Context in the Nature of Anatomical Movements*

One of the principles that emerge from a careful consideration of placement and movement is that the description of a movement may depend upon the context in which it occurs. Spin and swing are prime examples of that principle. Orientation and favored axes are central to most traditional considerations of anatomical movement. However, they are usually only implicitly defined and seldom dealt with explicitly. They are central to the approach introduced here.

Even the descriptors of the cardinal movements assume a particular context. Flexion and extension are generally unambiguous, because the sagittal plane is usually apparent and the axis of rotation is perpendicular to the sagittal plane. Right sideflexion of a vertebra implicitly assumes that the point of reference is the rostral face of the vertebra, that the rotation is about an axis pointing dorsoventrally, and that the direction of rotation is the direction that one's fingers curl if one's thumb points in the direction of the axis of rotation. Similarly, left lateral rotation is referenced to the ventral surface of the vertebra and an axis pointing rostrally.

The situation becomes more ambiguous when the movement is no longer in a cardinal direction. Rotation about an axis tilted midway between rostrally and ventrally pointing axes in the midsagittal plane is considered left lateral rotation and right sideflexion, whereas rotation about an axis tilted midway between a rostrally directed axis and a dorsally directed axis is a combination of left sideflexion and left lateral rotation. If the vertebra is tilted so that its ventral face looks caudally, then rotation about a strictly rostrally pointing axis is also considered right sideflexion and left lateral rotation. In fact, the situation is more complex than is implied by those descriptions. In order to see the full implications of such rotations it is necessary to introduce orientation frames and to be more specific about the axis of rotation.

Orientation of the vertebra is implicit in all of these movements. That is particularly true when we consider combined movements, such as lateral rotation with sideflexion. It makes no sense to speak in such terms unless one has orientation in mind. However, orientation is not usually mentioned when discussing these types of movements.

The context is usually the vertebral orientation, rather than the movement relative to the entire body. However, the interpretation of an anatomical movement may depend upon the assumed frame of reference. Turning the head from side to side in a horizontal plane while sitting in normal resting position will be a different combination of movements when referenced to the external world, the axis vertebra, or the body at the T1 vertebra. It is yet a different movement in the context of the semicircular canals, actually rather like the movement referenced to the T1 vertebra, which is also tilted about 30° ventrally or negatively about a transverse axis directed ipsilaterally.

As has been stated several times in the course of this book, it makes no sense to talk of left lateral rotation being in the same direction as left side flexion, as is often done. In fact, they are as little in the same direction as it is possible to be; they are orthogonal to each other. Also, in a right-handed coordinate system, left lateral rotation is a positive rotation and left side flexion is a negative rotation. In a left-hand coordinate system, the polarities would be reversed, but still opposite.

*Spin and Swing*

Spin and swing assume a prime anatomical axis for the object that is moving. When the axis of rotation of the object coincides with that anatomical axis, then the movement is called a spin. Otherwise the movement is a swing. If the reference point for the center of rotation lies in the plane of the rotation, then the rotation is said to be pure swing. Pure swing implies an axis that is orthogonal to the axis of rotation, and the movement occurs in a plane perpendicular to the axis of rotation. Since any unitary conical rotation can be rewritten as a planar rotation, by shifting the center of rotation along the axis of rotation, there is not an invariant spin or swing.

Often, the designated prime anatomical axis is not explicitly stated, nor is the axis of rotation or the center of rotation. Without that information, it is not possible to differentiate a spin from a swing. Whether a movement is spin or swing depends entirely upon the context in which it is being viewed. That is not to say that they are not useful concepts, only that one must be explicit about the context in which the movement is being interpreted.

*Shortcomings of the Traditional Approach*

The shortcomings of the traditional approach should have become evident from the previous sections. Too much is normally left unsaid, left to the reader's assumptions about the reference orientation and the default axes of rotation. The descriptions are exceedingly qualitative and minimally informative once we move beyond a consideration of the cardinal movements.

It adds little to my understanding to say that a movement is a combination of right sideflexion and right lateral rotation. It is not even clear what that means. Sideflexion and lateral rotation have definite meanings, if we agree on the directions of the cardinal rotations, but precisely what does it mean to have a combination of the two rotations. Rotation can occur in only one direction at any given time and if one is going to resolve it into component rotations, what is the protocol? Is there a single protocol and, if not, will the different protocols give the same result? If they give different results, how do we judge which one is the most appropriate?

Rotations can combine, as anyone knows who has ridden carnival rides that move about two of more centers of rotation at the same time. However, at any moment, the rotation is about a single axis of rotation. Also, one can move through a sequence of simple rotations to attain a particular location and orientation, but the experience is not the same as a single rotation about a particular center of rotation of even a moving center of rotation. The chapter on the application of the models of the lower cervical spine to finely divided complex movements illustrated how different the sequence of simple movements is from the smooth continuous movement.

*A Language for Describing Anatomical Movements: Frames and Framed Vectors*

The approach considered here was developed to circumvent the manifold limitations of the traditional approach and to introduce a language that allows an intuitive approach of great power and efficiency. It is a language that moves smoothly from anatomical description to the calculation of its consequences for movement.

The approach allows one to describe location, extension, and orientation unambiguously and rotations in such a manner that one literally computes with the anatomical description. The central element of the approach introduced here is the description of the anatomy in a manner that leads easily and naturally to computation of movement. The basis of that approach is distinguishing the different spatial attributes of an anatomical object and codifying them in terms sets of vectors. The framed vector is the principal tool. Location is differentiated from extension and both are differentiated from orientation. The distinctions are subtle, but important. Each transforms differently with anatomical movement.

A critical component of the approach is the use of quaternions to express the axes of rotation and the rotations of anatomical movement. Quaternions operate upon the vectors of the anatomical description to determine the manner in which the anatomy is transformed by movement and by including the axes of rotation as part of the anatomical descriptions, one can concatenate multiple anatomical objects into a chain of interacting objects that move in particular ways subject to the constraints imposed by their anatomy. The cervical spine provides a number of tractable problems that can be readily studied by such modeling and computation.

In the case of the lower cervical spine, it was possible to write down a description of the elements of the spine and concatenate them into a kinetic chain by specifying how they move relative to each other. Simply by specifying the amount of movement in each joint one automatically obtains the configuration of the entire spine. Describing the upper cervical spine allowed us to ask questions about the anatomy of the region that bore on the strain in the vertebral artery in any anatomical situation and the role of the alar ligament in restricting lateral rotation in the atlanto-axial joint. The description of the eyeball with its attached extrinsic muscles allowed us to ask several questions about the actions of the muscles, the roles of the fascial slings in the suspensory ligament and the control of eye movements.

The language of frames, framed vectors and quaternions provides a natural, intuitive, powerful language that allows analysis on multiple levels from literal hand waving to very complex and exact calculations. The precision of the output reflects the level of detail of the input. The anatomical description implies the anatomical movements associated with the anatomy.

While being quantitative can be daunting to many, the clarity of the answers is well worth the effort of creating the description. In addition, the results can be expressed in three-dimensional images of the anatomy. Since the conformation of the relevant anatomy is implicit in its description, one can move directly from the numerical description of the anatomy to an image.

*Soft Frames and Flow in Anatomical Materials: The Deformation of Boxes*

In the latter part of the book, we considered a rather different use of frames to describe a different type of anatomical movement, strain and flow. By attaching deformable frames to locations in a medium it is possible to describe the consequences of particular anatomies for flow in the medium. Because these frames are rather different from the rigid, non-localizable, frames of the first part of the book they are given a different name, boxes.

At this time, this area of inquiry is less developed than that concerned with rigid frames and I am still feeling my way by exploring the possibilities of particular anatomies and constraints. It is less formed, but worth considering as a different application of the basic principles that started the inquiry into anatomical movement. I think that it will give some interesting insights into the nature of anatomical movements as we explore more situations.

This approach seems to lead naturally from a description of local properties associated with strain to global properties, such as flow and flow lines, changes in contour, and probable loci for fracture. As with all quantifiable computational models, the exercise of creating the description of the anatomy forces one to consider many features of the situation that would otherwise slip below the radar. Often, those features that are assumed to be understood in a qualitative model are highly relevant to an understanding of the anatomy. Not infrequently, the assumptions turn out to be incorrect or the anatomy not precisely as assumed. For instance, it is only when examined closely that one discovers that spin and swing are contingent upon unstated assumptions about the structure of the moving object.

*In Conclusion*

There are great benefits to be realized by being careful about the concepts that one uses and about the language in which one frames questions. Often, once those factors have been considered, the solution of the problem flows readily from its statement. The approach introduced here is an attempt to develop those skills.

The process of developing a mathematical model is often illuminating in itself. It forces one to consider the details that may be critical to understanding the processes involved. Hand waving as a way of dealing with difficult concepts is no longer acceptable. Mathematical modeling may eliminate possible models that do not stand up to close scrutiny or which fail only when realistic numbers are substituted for its variables.

If the situation is described in an appropriate mathematical language, then the conclusions may be expressed much more clearly. A quantitative description will usually lead to a quantitative solution. A quantitative solution may be necessary to a clear understanding of a phenomenon under study.

It is by actually computing the changes in frames of reference that one comes to see that the process is more complex than is implied by a statement that there is a combination of right lateral rotations and left sideflexion. One is forced to think about what it means to say that there is sideflexion when the axis of rotation is not in a cardinal direction or the object is not aligned with the cardinal axes. One is forced to come up with a means of expressing the relative amounts of sideflexion and lateral rotation. Qualitative labels may prove inadequate for fully expressing the nature of the movements.

We have clearly just scratched the surface in dealing with the implications of this approach and have only the broadest notions of what it means to control placement or how a flesh and blood nervous system might go about doing so in a flesh and blood organism. That is where the excitement lies in the future applications of these ideas to anatomical structure and its movements.