A Biomechanics-Based Model for the Animation of Human Locomotion

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Abstract

The paper presents a model of an articulated figure for use in the animation of human locomotion. This model is an evolution of the standard hierarchical joint-based representation of a human figure, which is widely used in figure animation. Whereas previous models have been based on a simplified mechanics-based view of the joints, our model is based on an anatomical approach. This model uses physically-measured data of the behaviour of human joints and allows the simulation of such important attributes of real joints as combined motions and moving axes of rotation these are well known in biomechanics but have not previously been used in figure animation. We identify the joints for which it is important to simulate these features and analyse how they can affect the visual impression of animation.

Keywords: *Figure Animation, Articulated Figures, Joints, Combined Motion.*

1. INTRODUCTION

The animation of articulated figures is a rapidly-growing area of computer graphics. Several approaches to animating virtual characters have been developed, such as motion capture, methods based on kinematics and dynamics, or combined approaches, [1]-[4]. All of these methods use very similar models for the articulated figure, which is represented as a set of rigid links connected by joints.

The models (frequently called hierarchical models) are organised in a form of a tree; the nodes of the tree correspond to the links, and the edges correspond to the joints. The purpose of the joint connecting two links is to perform a transformation of one link relative to another. So the absolute position of a particular link can be calculated by concatenation of the transformations in all joints along the path from the root link to the current link.

This hierarchical model of articulated figures came into animation from robotics. All joints in these models are usually considered to have only one degree of freedom (a limitation that came from robotics), which is rotation about the axis. Joints with more than one degree of freedom are represented as several hinge joints connected by zero-length links. So motion in such a joint is simulated as two or three successive rotations about axes of the fixed orthogonal reference frame.

This type of model is highly suited for robotics, where joints are carefully constructed to have particular degrees of freedom, but this does not guarantee that it is appropriate for figure animation. It is obvious that the structures of real joints are quite different from those of mechanical joints; as will be shown below, there are also differences between the motions produced by real joints and by mechanical joints. To do this, we examine some assumptions made in hierarchical models:

- axes of joints are parallel to the anatomical axes of the figure (figure reference frame) this means that all basic motions (or any motion in a joint with one degree of freedom) are performed in either the ***frontal*** or the ***sagittal*** (vertical plane which divides a body into two symmetric parts) or the ***transverse*** (horizontal) planes
- the axis of rotation of a joint does not change during the motion.

In practice, these assumptions are not quite correct - the following table gives some indication about their validity.

Joint and articulation	Inclination of axis in one or two planes	Motion of the axis
knee flexion	-	15°
Ankle plantarflexion	10° and 25°	-
Inversion in the subtalar joint	42° and 16°	-
Flexion in the meta-tarsophalangeal joint	varies in range from 17° to 36°	-

Table 1 : Overview of motions in the normal lower limb.

As can be seen from this table, the approximation that all motions are performed in the reference planes and that all axes are immovable is an oversimplification. Therefore, in our research, we are trying to simulate the joint more accurately by taking into account effects which are specific to real human joints, including both combined motions and instant axes of rotation.

2. BIOMECHANICAL BACKGROUND

This chapter gives a short description of joint structure and function. The main joints of human lower body are further described in Chapter 5. A detailed description of joints from the biomechanical point of view can be found in [5, 6].

2.1 The structure and function of a joint

A joint is a bodily component used to connect the bones of the skeleton. Apart from connectivity, joints also provide mobility and stability.

The structure and function of joints are closely connected. The structure defines the character and range of motion available to the joint and thus it heavily influences the function of the joint. Although we do not simulate joint structure in our model, it is necessary to understand how joints are organised in order to simulate their function properly.

2.2 Joint structure and range of motion

The organisation of a synovial joint (the most frequent type of joint in the human) is not simple. On one hand, the joint should be stable and prevent the bones from disconnecting, but on the other hand, it should also allow them to move. This is achieved by means of a joint capsule which encloses the ends of the bones and thus connects them, but not in a rigid manner. In order to obtain additional stability and strength for a joint the bones are also connected by ligaments.

The character and range of motion in a joint is determined, to a considerable extent, by the cartilaginous surfaces which cover the ends of the bones.

Other factors influencing the range and orientation of joint motion are the ligaments connecting the bones, and the joint capsule. Also, it is obvious that the muscles will have some effect on the range of joint motion.

2.2.Types of joints.

Most joints in the human body permit some form of motion, though there are some which do not. The former are divided into three groups uniaxial, biaxial and multiaxial on the basis of the motions which can take place.

A ***uniaxial*** joint has one degree of freedom, rotation about an axis, e.g. the interphalangeal joint of the fingers. A ***biaxial*** joint allows a motion about two axes, e.g. the knee joint. ***Multiaxial*** joints have three degrees of freedom which can be rotations, as in the hip joint, or gliding, as in some spine joints.

Note that this classification is simplified; most joints show supplementary motions of small amplitudes. In some cases, multiple joints are organised into a unique functional joint, e.g. the midtarsal joint (in the mid-foot) is a compound of three joints.

2.3 Instant axis of rotation.

Although it is often assumed that motion in a joint is a simple rotation about a static axis, this is not really true. The axis of rotation does not stay the same, but continually changes throughout the motion so that at any moment the rotation is being performed about an instant axis called the IAR (instant axis of rotation). Thus, it is necessary to have a set of axes of rotation in order to simulate the joint motion properly. However, in many cases the change between axes is very small and a single axis is a reasonable simplification when simulating the motion the error induced depends upon the joint and the type of motion.

Note that the idea of an instant axis of rotation can be used to model complex simultaneous motions in a multiaxial joint. For instance, a motion in the hip can be modelled either as a sequence of three rotations about three axes or as a single motion about the instant helical axis.

2.4 Combined motion.

When you perform a motion in a joint, you can see that apart from the primary motion (the motion that you control), some ***secondary motions*** occur simultaneously with the primary one. For instance, a flexion of the knee is accompanied by its rotation. Such secondary motion is also called ***combined motion*** [7].

In contrast to the primary motion, you are not in control of the combined motion it is controlled by the character of the joint surface and the tension of ligaments rather than by signals from the central motor cortex. The combined motion can also occur as result of motion in several joints that form single joint complex.

Note that there is also so-called associated motion which occurs in several joints. This motion is also automatic and is caused by the tension of two-joint muscles (muscles that can move two joints).

In most cases, the amplitude of the secondary motion is much smaller than the amplitude of the primary motion. Nevertheless, it is significant for example, the amount of automatic rotation accompanying a knee flexion of 150° is approximately 15°.

3. THE FIGURE MODEL

The model of the articulated figure presented is an evolution of the standard hierarchical model, which is frequently used in figure animation. It supports combined motion and instant axes of rotation. Accurate data is a very important part of the model.

The following description covers the general features of the model but does not include features specific to some particular animation methods. For instance, if a dynamics-based method is used, the model should include information about the location of the mechanical axis, the location of the centre of mass, etc.

The model consists of three main types of object. The first object is ***Figure***. This contains all of the general parameters that define the properties of a figure as a whole, rather than properties of particular part of the figure. For example, it encapsulates such parameters as speed, step length, height, etc. *Figure* has its own local reference frame. It also embeds links to the two other kinds of objects: ***Link*** and ***Joint***.

The organisation of *Links* and *Joints* was inherited from previous models they are organised in a form of tree. A fragment of such a tree is shown in Figure 1.

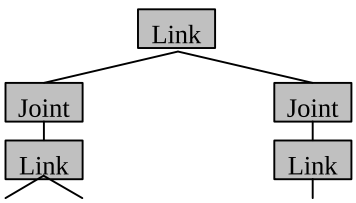


Figure 1: Fragment of model structure

This hierarchical representation defines the order in which transformations are performed. Each *Joint* and *Link* has its own reference frame objects; all of these frames are defined relative to each other by transformations from the frame of the parent object to that of the child object. Finally, the *Figure* knows its transformation to the world reference frame.

The object *Joint* works like a real joint. It encapsulates all the information about motions available in the joint. More precisely these include:

- definition of the joint reference system (transformation to/from the reference system of the parent link)
- definitions of axes the axis can be either an instant axis or a single axis; this definition includes also values that define the range of the described motion
- current state of the joint (current transformation, current angle of rotation, etc.)

Both basic motions and complex motions (primary and secondary) are performed in the same way, as a rotation about a single helical axis and a translation along this axis. In case of an instant axis, the rotation is performed in two steps. The following example illustrates these steps (translation is ignored here):

Let us assume we have measured axes for each 5° in interval from 0° (initial value) to 60°. We want to perform a rotation of 32°. This motion can be represented as a rotation from 0 to 30° and a rotation from 30° to 32°.

1. **Six consecutive rotations of 5° about the first 6 axes are applied; to speed up calculations, transformations corresponding to all of these rotations are pre-calculated.**
2. **A rotation of 2° is then performed about the 7th axis.**

In contrast to the *Joint* object, the *Link* object does not correspond directly to a real part of figure (usually it is assumed that the links correspond to the bones). The main purpose of this object is to provide the local reference frame, which is used to specify the position of joints, mechanical axes (bones), visualisation data, etc.

4. JOINT MEASUREMENTS

In order to simulate joints properly it is necessary to know their parameters. The following parameters are required for our model:

- ***Joint reference frame***. This frame is specified relative to the frame of the parent joint by a transformation from one frame to the other. If all measurements are performed in one frame it is quite simple to find this transformation. The situation becomes much more complicated if measurements are performed in different reference frames.
- ***Axis of rotation***, or a set of axes representing instant axes of rotation. Axes must be specified in the joint reference frame. The range of an angle of rotation must be given for each axis. For a single axis of rotation, this range limits the magnitude of the motion available; for the instant axis of rotation, this range indicates the interval over which the axis is applicable.

There are several approaches to measurement of joint motion. The main approaches are:

- ***Analysis of motion-captured data***. In this method the 3D positions of markers on the joints are tracked and the parameters of their motions are reconstructed. The benefits of this method are its non-invasive nature and the fact that it allows the joint reference frame to be located easily. Nevertheless, this method has drawbacks, the most significant of which is the relatively low accuracy - the markers are set on the skin and thus the slipping and stretching of the skin during the motion introduces some errors.

- ***Analysis of a set of tomodensitometry scans***. The idea of the method is to make several scans of the joint area and then directly track the motion of the bones [7]. Although this method can be more accurate than motion capture, it demands that the subject is X-rayed several times, so it cannot be used *in vivo*.

- ***Analysis using data from a 3D electrogoniometer***. This is the most accurate and straightforward method. The goniometer is fixed on to the subject s body; it then automatically tracks any motion in the corresponding joint. This method requires additional efforts to locate the joint reference frame, which coincides with the local frame of the goniometer. This method is used to acquire data for our model the data are measured by means of the electrogoniometers (Figure 2) with 6 degrees of freedom, which were developed at the University of Brussels [8].

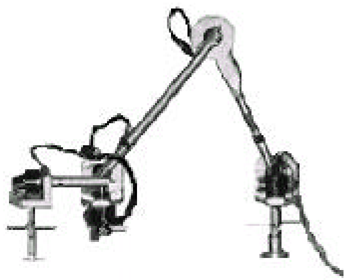


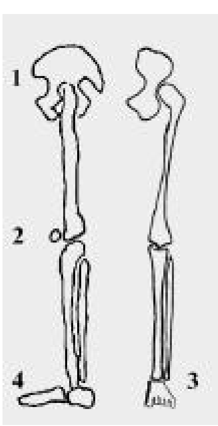
Figure 2: Electrogoniometer.

Although measurement of the joint motion by means of the goniometer can be performed rapidly, the whole measurement process, including the location of the goniometer frame, etc., is very time-consuming. Thus, it is necessary to re-use the measured data, when possible. Applying the data from one subject to the model of another subject requires the location of the joint frame to be re-calculated and the motion data to be scaled.

5. JOINTS OF THE LOWER LIMB

The major joints of the lower limb are presented here, with an emphasis on the definitions of joint axes and degrees of freedom. At present we have measured data only for the knee, so the description of the other joints is based on data found in the biomechanics literature, [5, 6].

There are four main joints in the human lower-body: the hip, the knee, the ankle and the foot joints, Figure 3. All of these joints are very significant for walking and therefore they will all be examined here.



1. Hip joint
2. Knee joint
3. Ankle joint
4. Foot joint

Figure 3: Anterior and lateral views of lower body

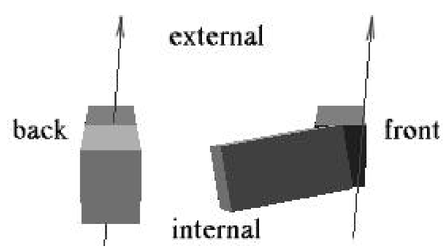
5.1 Knee joint

The knee joint is a good example of both combined motion and instant axes of rotation. Although it is referred to as a hinge joint, the knee is quite different from its mechanical analogy. The complex asymmetric surfaces of the bones (see Figure 4) and the system of ligaments produce motions in the joint which are rather complicated.

Figure 4: The articulating surfaces of the knee

The main articulation of the knee is flexion. This motion mainly takes place in the sagittal plane, but there is also a combined rotational motion. The total amount of this rotation associated with full flexion is approximately 15°.

The flexion axis of the knee is not only inclined but it also moves during the motion. Figures 5 & 6 illustrate the effect of combined motion and a moving axis of rotation using simple geometrical models. The data used was collected using an electrogoniometer, as noted above.



(a) **(b)**

Figure 5: **(a)** the extended knee
(b) the knee in the flexed (76°) position.

As can easily be observed in Figure 5, the rotation of the cube is not performed in one plane - this is caused by the combined rotation.

In Figure 6, the effect of the instant axis of rotation is clearly seen: the arrow representing the axis of flexion changes its orientation.

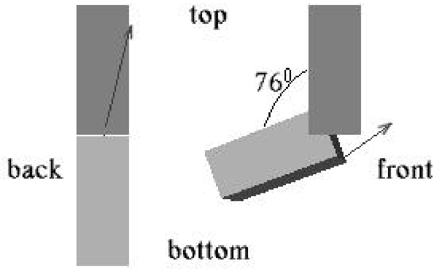


Figure 6: Side view of the same model.

Although it cannot easily be seen in Figure 6, the motion is actually not pure rotation, there is also a small component of translation.

It is thus clear that, in practice, the motion of the knee is considerably different from that of a simple hinge, which is its conventional representation in figure animation. We can thus expect that using accurate axes for the knee motion will lead to a noticeable difference in the character of the animation.

The knee joint has two further degrees of freedom : *rotation* in opposition to the combined rotation mentioned above (this motion is voluntary), and *abduction/adduction* (motion in the facial plane). However these are not very interesting for our model because they do not occur during walking and running activities.

Note that if one wishes to simulate atypical gaits (such as knock-kneed and bow-legged), the orientation of the axes of the leg should be considered in detail.

5.2 Hip joint

The hip joint is a ball-and-socket joint and has three degrees of rotation. It is not an ideal ball-and-socket, but it works almost like its mechanical counterpart. So we can approximate its axes as the axes of the orthogonal reference frame with a centre at the centre of the joint.

In contrast to the knee joint, all three degrees of freedom in the hip are very important, even for straightforward walking. Together with the flexion/extension motions, the participation of which in walking is obvious, both a motion in the frontal plane and a rotation should be considered in the simulation. These are part of the gait determinants [5], which help to minimize the energy losses during walking by reducing the amount of vertical and transverse movement of the centre of gravity of the body. As far as figure animation is concerned, including these motions greatly helps to make the animation more natural.

The other relationship which should be considered during the simulation is that between the motion of the hip and spine-pelvis joints. Motions of the hip are usually accompanied by motion between the vertebral column and the pelvis and vice versa.

5.3 Ankle and foot

The ankle-foot complex is a structure which unites several joints of the bottom part of the leg. Because the structure of the foot is quite complex (it contains about 30 bones), the motions within this formation are closely dependent. As a result, the character of motions of the foot is very complicated. Combined motion takes place in all joints of the foot. Moreover, sometimes the magnitude of the combined motion is so large that it is hard to tell the combined motion from the primary one.

Although there are many articulations in the complex, we consider only the three main articulations. These are :

- plantarflexion/dorsiflexion in the ankle joint,
- inversion/eversion in the subtalar joint,
- flexion/extension of the metatarsophalangeal joint.

Figure 7 illustrates the difference between the mechanical and anatomical views of the foot. The solid lines correspond to the real axes of rotation and the dashed lines to the simplified orthogonal axes. It is easy to see that the difference between the real and simplified axes is very large (the inclination of the axis of the subtalar joint (2) is about 42°). Thus, it seems very likely that the real motion and the motion simulated by means of simplified model will be quite different.

While the ankle joint is included in almost all figure models, the subtalar joint and the metatarsophalangeal joint rarely are. However, they play an important role in human locomotion, so it is worthwhile considering them, too.

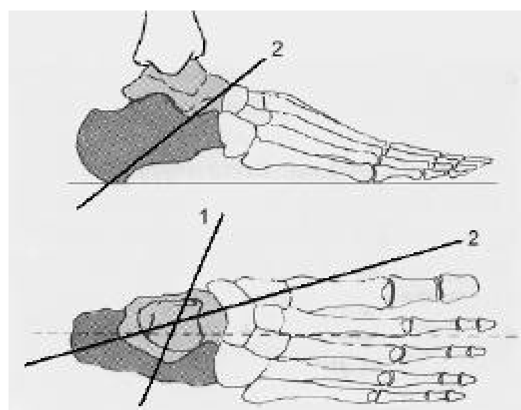


Figure 7: The ankle-foot complex.

The biomechanical functions of the joints in the ankle and foot are to provide additional degrees of freedom, absorb the shock of weight bearing and smooth the motion. However, if you look at the animation of many computer-generated characters, you will see that they lack these features: they walk like skiers in heavy, rigid ski boots. The proper simulation of the main articulations of the foot can make the motion of the character smoother and more natural. Note that, even if accurately specifying the axes of rotation does not produce noticeable effects in the foot of the free limb, it will do so in the case of the weight-bearing limb, because the rotation here results in movement of the torso, because the foot is fixed on the ground.

6. CONCLUSION

A study of joint motion from biomechanics has demonstrated that human joints behave considerably differently from the mechanical models generally used for figure animation. This may explain why motion, particularly that derived from kinematics- or dynamics-based approaches, often tends to look rather stilted and unrealistic. In our research we are trying to develop a model of a human figure which represents more accurately the way that human joints behave than figure models currently used in character animation.

To accomplish this, we simulate such features of the joints as combined motion and instant axes of rotation. These features have proved to be important in biomechanics applications.

The visualisation of these effects on models of the bones and on simple geometrical primitives shows that they are noticeable. However, it is remains to be proved that their use for the animation of a full body model will improve the visual appearance of the animation sufficiently to justify the additional complexity of the resulting model. At present, we are developing the model for the animation of human walking. The method of figure animation will be based on kinematics and motion-capture technologies. In particular, in our work we shall try to combine two-dimensional data from motion capture with accurate goniometer data.

Acknowledgement

Figure 4 is reproduced from: P. Abrahams, R. Hutchings, S. Marks Jr. *McMinn s Colour Atlas of Human Anatomy. 4th edition*, pp. 261-263. 1998

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