Forward Dynamic Model of Human Gait – A Tutorial

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Hi, I am Negar. I am a M.Sc. of control engineering student at K. N. Toosi University. I am a researcher at ARAS laboratory and my interested subjects are Haptic devices, teleoperation systems and surgical robotics. This Tutorial is project of Neuromuscular Systems Control score that presented by Dr. M. Delrobaei. The material in this tutorial is about Forward Dynamic Model (FDM) and its application in human gait. In this tutorial, my purpose is to introduce you the concept of FDM and then FDM of human gait. (My Email: negarhojati@email.kntu.ac.ir)

First question is, “Why we use Forward Dynamic Models?”. The answer is that, we use FDM because of three reasons, first Validation, second Understanding and third Prediction.

- **Validation**: do forces estimated from inverse dynamics reproduce the observed motion?
- **Understanding**: how do muscle forces generate motion – what are the “cause and effect” relationships?
- **Prediction**: “what if” a muscle or joint is altered, how will performance change?

**Key Concepts**

- Musculoskeletal model dynamics
- States of a musculoskeletal model
- Controls of a musculoskeletal simulation
- Numerical integration of dynamical equations

![Figure 1](image-url)
Musculoskeletal model dynamics

States of a musculoskeletal model

- States are model variables that are governed by the dynamics
- All measures of interest can be calculated from the states

Controls of a musculoskeletal simulation
Numerical integration of dynamical equations

FDM of Human Gait

Human and animal gait has been studied by using experiments to tease out the neural, muscular and mechanical mechanisms that are employed to walk. Inverse dynamic simulation is the most common simulation technique used to study human gait. Inverse dynamics works backwards from an observed motion in an effort to find the forces that caused the motion | inverse dynamics is not predictive. In contrast, forward dynamics can be used to determine how a mechanism will move when it is subjected to forces | making forward dynamics predictive.

Unlike inverse dynamic, in forward dynamic forces that drive the system are regarded as known, while the motion is derived by solving the equations of motion. First start with a model of the rod for dynamic analysis using forces expressed in the inertial coordinate system ("Inertial-based approach"). A slender rod with concentrated moments and forces at the bottom and top was used.

Figure 1
These equations are coupled, and some equations are nonlinear due to the trigonometric terms. Many solutions are possible, depending on the initial conditions imposed. A straightforward symbolic integration is therefore extremely difficult, and a numerical solution is the only option.

The method of integration used was the Modified Euler Method. This technique involves two predictive iterations of integration. The current acceleration is calculated from the forces (and current position, if necessary) using the equations of motion shown above. The current acceleration and velocity are used to predict the velocity and position for the next instant of time.
Further repetition of estimating and averaging would improve the quality, and many techniques actually involve an indefinite number of iterations until the resulting values converge (or diverge, in which case other alternatives must be implemented, such as reduction of the time increment).

Similar to the rod simulation, the methods involved in developing a predictive model of human locomotion can be divided into four sections: experimental procedure, data reduction, inverse dynamics analysis, and forward dynamic synthesis.

Experimental procedure

The environment calibration and data collection procedure was performed using the same equipment described in last section. Again, motion was collected at 60 Hz and force was collected at 1000 Hz. The calibration space used was again established by 16 stationary targets, but varied in size for each subject, and the procedure for establishing dimensions for the space were as follows: The length of the space (x direction) was estimated as 20% longer than the stride length of the subject, the space centered about the gait cycle beginning near foot strike and ending near the second foot strike of the same leg. The width of the space was one meter wide, and the height was estimated as 20% higher than the subject’s superior iliac spine, to assure sufficient assessment of pelvic motion. The environment was positioned so that the force plate was centered in the width of the space and near one end of the length (approximately 10% of the length) so that the first foot strike fell on the force plate.

Figure 2: The environment used showing the lab (inertial) reference frame
Anthropometric data was obtained on each subject through measurements. The experiment was conducted on several subjects that walked at a normal pace through the environment. Trials were discarded if the subject failed to remain in the space or strike the force plate cleanly with one foot. For consistency, all trials were collected with the subjects barefoot. The data for each trial was shortened to approximately 10% before and 10% after the gait cycle.

Data reduction

The data reduction phase is similar to that of last section that each body segment’s position, velocity, and acceleration were determined in the same way as the rod.

Each body segment possessed a distal and proximal joint vector. The convention used is shown in Figure 5 and the specific definitions are summarized in a table. The vectors were expressed in the principle coordinate system of the body segment, originating at the segment’s center of mass.

Figure 3: The targeting protocol used

Figure 4: The convention used for link-segment analysis
Now we should consider “Data Reduction” section for foot, leg and thigh. Let’s start with foot.

➢ The foot

The foot motions were calculated by averaging the two rearfoot target positions, establishing a distal landmark, and using the calcaneal target as the proximal landmark. The foot segment coordinate system was then established as a vector from the foot distal landmark to the proximal landmark (foot z axis) and a vector perpendicular to the z axis and the inertial y axis, directed according to the right hand rule.

![Foot analysis from targeting](image)

Figure 5: Foot analysis from targeting. a) bottom view. b) side (in-plane) view

➢ The leg

The leg analysis, summarized in Figure 7, was performed by using the distal and proximal targets, mounted along the tibial crest. This was assumed in alignment with the principle coordinate system of the leg.

![Leg analysis from targeting](image)

Figure 6: Leg analysis from targeting
The thigh analysis is illustrated in Figure 8. The principle long axis (z) was established by a line between the lateral condyle and the greater trochanter targets.

Figure 7: Thigh analysis from targeting

**Indirect Dynamic**

The increase in complexity from a single slender rod to a system of interconnected rigid bodies

We need several changes to the equations of motion

**Note**

The equations had to accommodate non-slender segments where the centers of mass and principle long axes did not necessarily lie on a line between the distal and proximal joints
A net effect of both of these parameters was calculated: \( M_{\text{passive}} \). Setting the spring and damping coefficients to zero assumed no contribution of passive elements \( (M_{\text{passive}} = 0) \).

Forces were expressed in the body segment coordinate systems due to the success of such an approach using the slender rod. Therefore, each equation of motion contained 2 dimensional transformations of forces to the inertial coordinate system, so that motion was determined relative to the inertial reference. A convention was adopted where all forces acting on the proximal joint of a segment were expressed in the coordinate system of the segment. The equations of motion for each planar body segment moving in the inertial reference frame are:

\[
\begin{align*}
    m\dddot{X} &= (F_{Dx} + F_{Px})\cos\theta \\
    m\dddot{Z} &= -(F_{Dx} + F_{Px})\sin\theta + (F_{Dz} + F_{Pz})\cos\theta - mg \\
    I\dddot{\theta} &= (M_D)_{active} + (M_P)_{active} + (M_D)_{passive} + (M_P)_{passive} + (R_{Dz}F_{Dx} - R_{Dx}F_{Dz}) \\
                 &+ (R_{Pz}F_{Px} - R_{Px}F_{Pz})
\end{align*}
\]

where the subscript D denotes the force or moment at the joint distal to the segment, and P denotes the force or moment at the joint proximal to the segment. In the case of the foot, where there was no distal joint, the subscript G (ground applied force) was substituted for D in the above equations, and the COP\(^1\) position could be treated mechanically as a moving point where force is applied. The subscript

\(^1\) Position of the center of pressure
active denotes the contribution of the active or muscle moment and the subscript passive denotes the passive torsional joint spring damper elements.

Analysis began with the foot segment, where the forces measured from the force plate were used with measured foot accelerations to solve for forces and a moment at the ankle. The ankle forces and moment were reversed in sign to be used with the measured leg motions to solve for forces and a moment at the knee joint. The knee forces and moment were reversed in sign to be used with the measured thigh motions to solve for forces and a moment at the hip joint.

**Forward Dynamic Synthesis**

The addition of new segments to the model required the adoption of several conventions with respect to forces and motions. As mentioned above, joint force was expressed as applied to the segment immediately distal to it, in the coordinate system of that segment, as shown in Figure 9. Ground applied forces (GAF) and moment (GAM) are expressed in the inertial coordinate system.

![Figure 8](image)

Unlike the indirect analysis, the assumption was made that each joint (the knee and ankle) was an ideal hinge. The addition of segments connected by hinge joint constraints required the simultaneous solution of the equations of motion subjected to additional equations of constraint. The acceleration of the joint was expressed in terms of the motions and the joint position vectors of the two segments which the joint connects:
The subscript a refers to the segment distal to the joint and subscript b refers to the segment proximal to the joint.

The effects of passive element contributions (joint torsional spring and torsional dampers) on system motion were included in the equations. Each torsional spring and damper was consistent with those used in the indirect dynamics solution, and was included in the equations of motion. A calculation of the joint angle and joint angular velocity was required for every instant in order to calculate the passive moment values.

The method for solution was chosen as a simple linearization and integration technique, outlined in Figure 10. The integration process began with initial conditions manually specified or determined from the original measurements of motion.

\[
\ddot{\rho}_a + \ddot{\alpha}_a \times \dot{R}_{pa} + \dot{\omega}_a \times (\ddot{\omega}_a \times \dot{R}_{pa}) = \ddot{\rho}_b + \ddot{\alpha}_b \times \dot{R}_{db} + \dot{\omega}_b \times (\ddot{\omega}_b \times \dot{R}_{db})
\]
References:


Reference of Pictures:


Reference of Charts:

Charts have been made by myself.