Functional Assessment of Biomechanics System: Human Body Inverse Dynamics Using Inertial/Magnetic Motion Capture

The FAB system is an integrated motion capture device capable of measuring static body positions as well as dynamic human motions. Since the days of Isaac Newton, it has been well understood that the dynamic motion of a body, or specifically its acceleration, is intimately related to the applied force via the equation *force = mass x acceleration*. The basic design of the FAB sensors, based on accelerometers and rate gyroscopes, enables clean and crisp estimates of acceleration to be made. This in turn makes the study of the forces and torques acting within the human body particularly fruitful. Nevertheless, there are limitations to the accuracy of such techniques related largely to the assumptions that must be made regarding the geometry and mass properties of the human subject, as well as the boundary forces acting on the subject from his interaction with the physical environment. This document briefly describes the inverse dynamical techniques employed and outlines some of their limitations.

THE HUMAN SUBJECT AS A NETWORK OF RIGID BODIES

The human subject is modeled as a network or linkage of body segments, as shown in Figure 1. The body segments are assumed to be rigid and all body motion is assumed to occur via rotation of the segments relative to each other at the points indicated by orange spheres. This assumption allows standard rigid body mechanics[i] to be employed. The internal forces, bending, or muscle motion within each segment can be neglected. Research has indicated that this assumption produces good results in most circumstances, especially if one is concerned with relative, rather than absolute, values of force and torque[ii].

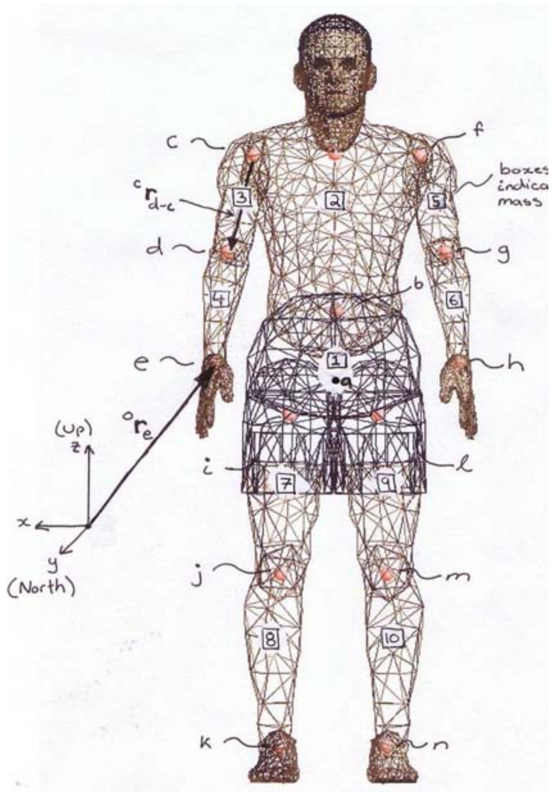

Fig. 1. Human subject as a network of rigid body segments

HUMAN BODY GEOMETRY AND MASS PROPERTIES

Many efforts have aimed at quantifying average human body proportions and mass segment properties that scale in simple and predictable ways with height and body mass. Wilfrid Dempster and George Gaughran performed a thorough study of the geometric and mass properties of the human body segments using direct measurements on nine male cadavers[iii]. FAB uses this data to determine body segment length, relative location of segment mass centers, and moment of inertia properties. By incorporating this data into the FAB software, the model of the human body becomes sufficient to apply inverse dynamical techniques, scaling with both height and weight in a sensible manner. As no data was available from female cadavers, male data is used in its place, scaled of course to the lighter average female weight. Finally, as the FAB system employs two sensors over the torso (lower back, and upper back), certain segments in the chest and stomach region were combined or modified to suit the two-segment torso model employed by FAB.

DETERMINING THE POSITION OF JOINT CENTERS

As previously described, the human subject is modeled as a network of rigid bodies connected with revolute (rotation only) joints. Therefore, the position of the patient in space is specified by the Euler angles (orientation) of each of the body segments measured against the stationary earth frame, uncertain only to a single translational vector. Since the FAB system measures the orientation of each segment, these measurements, along with our assumed model for the human subject, are used to determine patient position at any point in time. These calculations are carried out using standard 4x4 matrix multiplications, well known in the field of robotics, to determine the positions of all the body joints (e.g. shoulder and elbow) and body segment mass centers[iv].

DETERMINING THE JOINT FORCE

The joint reaction forces are found using Newton's second law applied to the individual body segments. The strategy is to start the analysis with the distal body segments, subject to boundary value forces from the environment. Based on their physical motion and the applied forces, it is possible to infer what that reaction forces in the segment's proximal joint must have been. The analysis then moves to the next body segment in the chain, with the previously determined force taken to act equal and oppositely on the adjacent segment, according to Newton's third law.

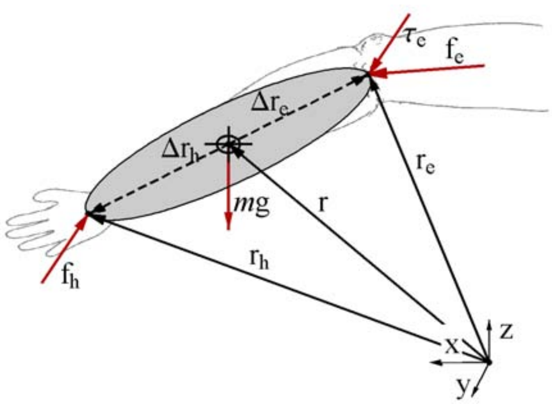

Fig. 2. Force diagram of lower arm

For example, consider the problem of determining the forces exerted by the upper arm body segment (elbow joint) onto the lower arm. The lower arm force diagram appears as shown in Figure 2: $\mathbf{f}_h$ is the external force applied to the hand, $m\mathbf{g}$ is the force of gravity acting on the segment, and $\mathbf{f}_e$ and $\boldsymbol{\tau}_e$ are the elbow force and torque, respectively. Applying Newton's second law

$$\mathbf{f} = m\mathbf{a} \tag{1}$$

to this body segment gives

$$_{h} + \mathbf{g} + m\,\mathbf{a} = m\ \cdot \tag{2}$$

Solving for the unknown elbow reaction force yields

$$\mathbf{f}_e = m\mathbf{a} - \mathbf{f}_h - m\mathbf{g}\ . \tag{3}$$

To determine the elbow reaction force, each term on the right hand side of Eq. (3) must be found. The weight term is found easily as the mass of the arm has previously been approximated and the gravity vector is a known physical constant. The acceleration can be found noting that it is the second derivative of the position of the forearm center of mass (CM). The first step is to determine the velocity of the forearm CM in discrete time

$$\mathbf{v}(t) = \frac{1}{2\Delta t}\left[\mathbf{r}(t+\Delta t) - \mathbf{r}(t-\Delta t)\right] \tag{4}$$

and then take a second derivative to find the acceleration

$$\mathbf{a}(t) = \frac{1}{2\Delta t}\left[\mathbf{v}(t+\Delta t) - \mathbf{v}(t-\Delta t)\right]\cdot \tag{5}$$

Multiplying this result by the lower arm mass produces the inertial term in Eq. (3). Lastly, the force applied to the hand, $\mathbf{f}_e$, cannot be measured or calculated, and, instead, its value must be assumed. Its magnitude and direction depend on the manner in which the subject is interacting with the environment and is specified by the user through options in the FAB GUI. It is described further in the "Boundary Values" section. With all terms on the right hand side of Eq. (3) specified, the elbow reaction force is directly calculable.

The next step in the mechanical analysis is to determine the forces in the shoulder joint. To do so, the upper arm segment is inspected, noting that the force applied by the lower arm to the upper arm is equal and opposite to $\mathbf{f}_e$—the force just determined. The force calculation for the other body joints proceed in a similar fashion.

DETERMINING THE JOINT TORQUES

A well-known result of Newtonian mechanics states that the net torque acting on a rigid body is equal to the time rate of change of the body's angular momentum:

$$\boldsymbol{\tau} = \frac{d\mathbf{L}}{dt}\cdot \tag{6}$$

Applying this law to the lower arm, measuring torques about the segment mass center, one obtains

$$\boldsymbol{\tau}_e + \Delta\mathbf{r}_e \times \mathbf{f}_e + \Delta\mathbf{r}_h \times \mathbf{f}_h = \frac{d\mathbf{L}}{dt}\cdot \tag{7}$$

Solving for the unknown elbow torque yields

$$\boldsymbol{\tau}_e = \frac{d\mathbf{L}}{dt} - \Delta\mathbf{r}_e \times \mathbf{f}_e - \Delta\mathbf{r}_h \times \mathbf{f}_h\cdot \tag{8}$$

The cross-product terms on the right hand side of Eq. (8) follow easily from the know force and positional data. The angular momentum is given by the equation

$$\mathbf{L} = \mathbf{I}\,\boldsymbol{\omega} \tag{9}$$

where $\mathbf{I}$ is the inertia tensor of the lower arm and $\boldsymbol{\omega}$ is the angular velocity of the lower arm, both expressed in the Earth frame coordinate system. The inertia tensor, known via the cadaver data, is constant only in the body segment frame. The time-dependent earth frame inertia tensor is found via the congruency transformation

$$\mathbf{I} = \mathbf{R}\mathbf{I}_{\text{body segment frame}}\mathbf{R}^{T}, \tag{10}$$

where $\mathbf{R}$ is the othonormal matrix that specifies the direction cosines of the lower arm coordinate frame relative to the earth frame. The angular momentum vector is now completely specified and its time rate of change follows easily via

$$\frac{d\mathbf{L}(t)}{dt} = \frac{1}{2\Delta t}\left[\mathbf{L}(t+\Delta t) - \mathbf{L}(t-\Delta t)\right]\cdot \tag{11}$$

Determining the remaining joint torques follows a similar calculation.

JOINT POWER

Joint power is defined as the vector dot product of the joint torque and the relative angular velocity of the adjoining body segments. It describes the mechanical power flow into (negative) or out of (positive) the joint.

BOUNDARY VALUES

The inverse dynamical techniques employed to determine joint forces and torques require assumptions to be made about the external forces acting on the subject. The FAB system deals with two such external forces. The first are the external forces applied to the feet, typically by the ground. FAB's weight bearing sensors measure the magnitude of this force but its direction remains unknown. The inverse dynamics package assumes that this force is applied coaxial with the lower leg. This is a reasonable assumption in many static situations as well as when motion is slow. However, it can produce significant errors when there are large torque components acting on the feet such as during a golf swing.

The second external force the FAB system deals with is the carrying load applied to the hands. FAB deals with both one-handed as well as two-handed carrying. In the former case, the system assumes that the specified weight being carried is a static force applied at the appropriate wrist. In the later case, the system assumes that the weight being carried is a static downward force split evenly between right and left hands, applied at each wrist. Significant errors can be expected if the load being carried is applied at a significantly different point than what is assumed, or if fast dynamic movement is involved.

REFERENCES

[i] Goldstein, H. (1980). *Classical Mechanics* (2nd edition). Addison-Wesley.

[ii] Nigg, B., MacIntosh, B., and Mester, J. (2000). *Biomechanics and Biology of Movement*. Human Kinetics.

[iii] Dempster, W., and Gaughran, G (1985): Properties of Body Segments Based on Size and Weight. *American Journal of Anatomy*, 120 pp 33-54.

[iv] Sciavicco, L, and B. Siciliano (2000). *Modeling and Control of Robot Manipulators* (2nd edition). McGraw Hill.