ESTIMATING THE GROUND REACTION FORCES IN THREE-DIMENSIONAL SIMULATION OF STANDING POSTURE

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Abstract
A technique for estimating the ground reaction forces in three dimension on the two lower limbs during bipedal standing in a neutral standing posture is discussed. The applications of the technique in the solution of different inverse dynamics problems in human standing, particularly with respect to modeling and simulation of FNS control systems, are highlighted.

Introduction/Background

One of the main problems in the biomechanics of human motion is that of determining the joint torques and the muscle forces needed to execute different activities. This is called the inverse dynamics problem. Many efforts have been spent in the solution of the inverse dynamics problem for two dimensional situations (often for movement in the saggital plane). Recently efforts are on to find solutions to the problem in three dimensions [1].

A number of powerful software packages are now available to the biomechanics community for the simulation and solution of problems related to this system. In particular, we are using SD/FAST (Symbolic Dynamics, Inc) for deriving the equations of motion; SIMM and Dynamics Pipeline (Musculographics, Inc) for linking the mechanical description of the system with muscle models and for graphic display and analysis.

In setting up the equations of motion for the system, one of two methods could be used. In the first method, the system is modeled as a closed chain in which the two limbs are fixed to the ground [1]. The differential equations of motion are then developed along with algebraic equations describing the closure constraint. The two sets of equations have to be solved simultaneously. This approach has a number of disadvantages: First, the integration of the equations could take longer periods owing to the need to keep the constraints satisfied. Secondly, the closure equation often requires that the distance between the two limbs be kept at a particular value. This restricts the possible postures that could be studied. Also, in trying to determine the joint torques using Dynamics Pipeline, it is required that all redundant coordinates have to be removed. This implies that the algebraic equations have to be solved in order to eliminate some of the coordinates. This can be a tedious process as the algebraic equations are highly nonlinear and the symbolic differential equations of motion generated by SD/FAST are not readily available to the user for manipulation.

The second method is to replace the ground-feet interaction with the actual values of the ground reaction forces (GRF). This has the advantage that there is no longer any need for the closure constraint equations. The main problem with this approach is that the GRFs will have to be determined using force-plate measurements. This is not feasible in situations where large numbers of possible postures are to be simulated. To get around the problem, we have developed a simple technique for estimating the GRFs from the geometry of the posture.

Methods

The coordinate axes used to define the dynamic quantities are shown in Figure 1. In deriving the system dynamic equations, it is assumed that the pelvis is fixed to the ground and the two lower limbs and the trunk are capable of rotating with respect to the pelvis according to the degrees of freedom at the various joints. The contact between the limbs and the ground is accounted for by introducing the ground reaction forces F_R and F_L at the right and left feet respectively. These forces are estimated by using the geometry of the standing posture to distribute the weight of the body between the two feet.

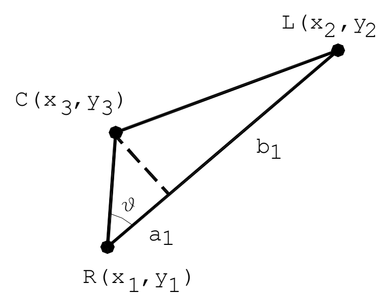

Figure 1: Location of the Right Toe (R) theLeft Toe (L) and the projection of the system Center of Mass (C).

The estimates are obtained in two parts, the vertical components and then the horizontal components.

Estimating the vertical GRF components: Any posture is defined by specifying the joint angles. The vertical components are estimated by first determining the x and z components of the positions of the two feet needed to obtain the given posture. Once the angles are specified, it is checked to confirm that the two feet are firmly planted on the ground (they have the same y coordinate). If this is not the case, an optimization algorithm is called to enforce that condition. In doing that some or all of the coordinates will be slightly adjusted until the condition is satisfied.

Thereafter, the vector position of the overall system center of mass is computed using the formula:

$$\vec{r} = \frac{\sum_i m_i \vec{r}_i}{\sum_i m_i}$$

Where $\vec{r}_i$ *and* m_i are the vector of the position of the center of mass of segment i and the mass of that segment respectively.

Let R(x_1, z_1) and L(x_2, z_2) be the coordinates of the right and left feet respectively on the ground. Let C(x_3, z_3) be the coordinates of the overall system center of mass projected to the ground (See Figure 1).

From the geometry of the figure, it is deduced that if RL = $\vec{a}$, RC = $\vec{b}$, then,

$$\vec{a}.\vec{b} = (x_3 - x_1)(x_2 - x_1) + (y_3 - y_1)(y_2 - y_1)$$

$$\left|\vec{a}\right| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$\left|\vec{b}\right| = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$$

$$a_1 = \frac{\vec{a}.\vec{b}}{\left|\vec{a}\right|}$$

$$b_1 = \left|\vec{a}\right| - a_1$$

From these, the estimates of the vertical components of the GRFs under each foot are estimated as functions of the total body weight W as:

$$F_{VR} = \frac{W\,b_1}{(a_1 + b_1)} \text{ and } F_{VL} = \frac{W\,a_1}{(a_1 + b_1)}$$

<u>Estimating the horizontal GRF components</u>: Horizontal components of GRFs only arise when the limbs are rotated away from the erect position (See Figure 2). The amount of displacements of the limbs along any of these directions are measured by the displacement of the left and right feet from the projected coordinates of the hip joint onto the assumed flat ground. The horizontal components of the GRFs are computed using the x and z coordinates of the feet. For instance, for the left foot shown in Figure 3, let

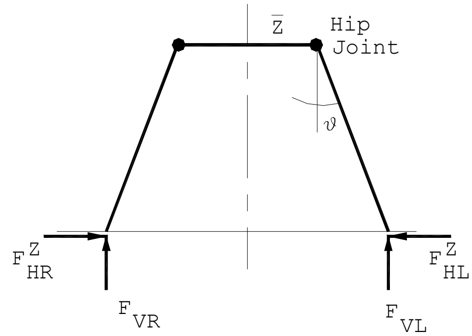

Figure 2: Horizontal components of the ground reaction forces in the frontal plane.

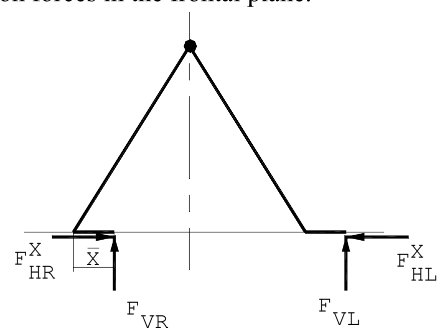

Figure 3: Horizontal components of the ground reaction forces in the saggital plane

(x_L, y_L, z_L) be the coordinates its position, then from the figure,

$$\tan\vartheta = \frac{z_L - \bar{z}}{y_L} \quad \text{and} \quad \tan\vartheta = \frac{F^Z_{HL}}{F_{VL}}$$

From which can be derived the following expression for the z component of the left GRF:

$$F^z_{HL} = F_{VL}\,\frac{z_L - \bar{z}}{y_L}$$

For the right limb a similar expression holds:

$$F^z_{HR} = F_{VR}\,\frac{z_R - \bar{z}}{y_R}$$

Using similar arguments, the following expressions for the x components are derived:

$$F^x_{HL} = F_{VL}\,\frac{x_L - \bar{x}}{y_L} \quad \text{and} \quad F^x_{HR} = F_{VR}\,\frac{x_R - \bar{x}}{y_R}$$

This method for estimating the GRFs was applied to a 3 dimensional anthropormetric model of an able bodied male. Model parameters (location and distribution of segment masses, segment inertias, and segment dimensions) for a male of average stature (1.8 m tall and 76 kg weight) were obtained from [2] (with the first and second inertia values in Table 1 of [2] swapped). Simulations were performed with the model in three different postures: 1) Neutral erect standing, wide stance with the hips abducted, and a tandem stance with the right limb placed in front of the left. Results were examined for internal consistency and physiological relevance.

Results

Simulation results are summarized Table 1. When the body is standing erect with a narrow stance, the dominant forces are the vertical ones and they are equally distributed between the two limbs. When the legs are spread apart through abducting the two hips, horizontal components along the z direction come into play. When the limbs are set such that the right leg steps forward and the left one behind, horizontal components in the x direction come into play. It should be noted also that for this case, the body is laying more on top of the left limb and hence the vertical components are distributed such that the left carries the heavier load.

Table 1: Simulated GRF components derived from the method described in the text (in Newtons)

Posture	Condition		R GRF	L GRF
Neutral Stance	Feet directly under pelvis	Horizontal x (N)	1.63	1.63
		Vertical y (N)	373.63	373.63
		Horizontal z (N)	3.59	3.59
Wide Stance	R & L hips abducted 20^o	Horizontal x (N)	1.73	1.73
		Vertical y (N)	373.63	373.63
		Horizontal z (N)	129.85	129.85
Tandem Stance	R hip flexed 19^o; R knee flexed 21^o; L hip extended 11^o	Horizontal x (N)	25.15	34.07
		Vertical y (N)	207.11	540.15
		Horizontal z (N)	0.19	12.38

Discussion/Conclusions

This method for computing the components of the ground reaction vectors under each foot in three dimensions appears to yield results that are reasonable and make physiological sense. Some modifications that could be introduced to further improve the estimates is to distribute the vertical component in each foot into two – one portion at the toes and the other at the heels to simulate the fact that the vertical components do not act at one point for most standing postures.

This method may be useful in performing simulations under a wide variety of conditions for testing novel control systems for automatically maintaining standing posture and balance with FES. In particular, once the ground reaction forces have been determined, it is straightforward to determine the joint torques needed to maintain a given standing posture. With this information, the individual muscle forces can be determined using a suitable optimization program. Being able to estimate the muscle forces is indispensable in studies that are aimed toward obtaining information on the effects of fatigue, loss of stimulation and application of electrical stimulation to the various muscles required to maintain a given standing posture.

Although the method remains to be verified experimentally, it is a very useful scheme for getting good estimates for the ground reaction forces; which would make simulations of standing postures in FES easier and faster to execute.

References

[1] Zhao, W, Kirsch, R.F., Triolo, R.J. and Delp, S., "A Bipedal, Closed-Chain Dynamic Model of the Human Lower Extremities and Pelvis for Simulation-Based Development of Standing and Mobility Neuroprostheses", *Proceedings, IEEE Engineering in Medicine and Biology Society*, Hong Kong, October 1998, pg. 2605-2608.

[2]Yamaguchi G.T. and Zajac, F.E., "Restoring Unassisted Natural Gait to Paraplegics Via Functional Neuromuscular Stimulation: A Computer Simulation Study", *IEEE Trans Biomed Eng*, 37: 886-902, 1990

Acknowledgments:

This work was funded by Contract #N01-NS-6-2351 of the Neural Prosthesis Program of the National Institutes of Health and grant #R01-NS-40547 from the National Institute of Neurological Diseases and Stroke.