Estimating Double-stance Ground Reaction Forces and Moments From Motion Capture Data Without Using Force Plate Measurements

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Abstract

Analyzing human movement through inverse dynamic modeling is a commonly-used method for extracting kinetic information such as joint torques and reaction forces. In such studies, force plates are often used to measure the ground reaction forces and moments (GRF&Ms). However, force plates are usually costly, time-consuming to set up, and can only cover a small area. In this study, a simple method for estimating the GRF&Ms by only using the kinematic data (motion capture data) without using any force measurements is proposed. This method is simpler and requires less kinematic information, such as exact motion data of the sole of the foot, compared to other methods in the literature [1, 2].

A 29 degrees-of-freedom human skeletal model is used in this study as shown in Fig. 1(a). The dynamic model of the human skeleton is obtained in the following form:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{Q}(\boldsymbol{q})\begin{bmatrix}\boldsymbol{F}_G \\ \boldsymbol{\tau}\end{bmatrix} \tag{1}$$

where $\boldsymbol{q}_{29\times1}$ is the generalized coordinates, $\boldsymbol{M}(\boldsymbol{q})$ is the mass matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ contains the Coriolis forces, and $\boldsymbol{G}(\boldsymbol{q})$ includes the gravity forces. Also, $\boldsymbol{\tau}_{23\times1}$ is the vector of joint torques and $\boldsymbol{F}_{G(12\times1)}$ contains the GRF&Ms exerted on both feet. Furthermore $\boldsymbol{Q}(\boldsymbol{q})$ is the Jacobian that maps the GRF&Ms and joint torques into the joint space. When performing inverse dynamic analysis, it is assumed that the motion of the body, i.e., $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$, is known and the objective is to obtain the joint torques, i.e., $\boldsymbol{\tau}$.

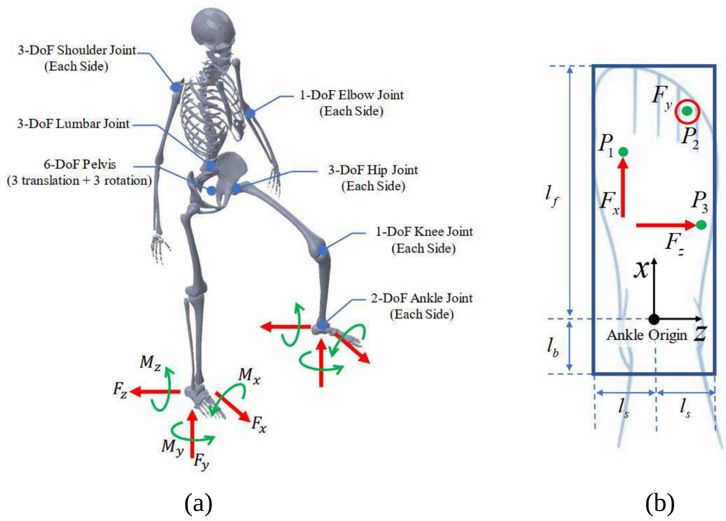


Figure 1: (a) Visualization of the skeletal model. (b) The resultant of ground reaction forces and their point of application (Top view).

During single foot support, the GRF&Ms can be obtained directly from Eq. (1) by setting the GRF&M on the airborne foot equal to zero. However, when both feet are in contact with the ground, the total number of unknowns (35) exceeds the number of scalar equations (29).
As shown in Fig. 1(b), the position of the resultant of the ground reaction force distribution in x-, y-, and z-directions are respectively assumed to be at $P_1(x_1,-h,z_1)$, $P_2(x_2,-h,z_2)$ and $P_3(x_3,-h,z_3)$ described in the ankle local coordinate frame. Hence, one can obtain the moment of the forces about the center of

the ankle as:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} -z_2 F_y - hF_z \\ z_1 F_x - x_3 F_z \\ x_2 F_y + hF_x \end{bmatrix} \tag{2}$$

Considering that the reaction forces should be inside the supporting area of the foot, and using Fig. 1(b), one can obtain the following constraints for the moments in Eq. (2) as:

$$|M_x + hF_z| \leq F_y l_s \tag{3}$$

$$\left| M_y - \frac{1}{2}\left(l_b - l_f\right) F_z \right| \leq |F_x| l_s + \frac{1}{2}\left(l_b + l_f\right)|F_z| \tag{4}$$

$$\left| M_z - hF_x - \frac{1}{2}\left(l_f - l_b\right) F_y \right| \leq \frac{1}{2}\left(l_b + l_f\right)|F_y| \tag{5}$$

Furthermore, considering that the normal force should always be positive and assuming no slipping on the ground, one can write:

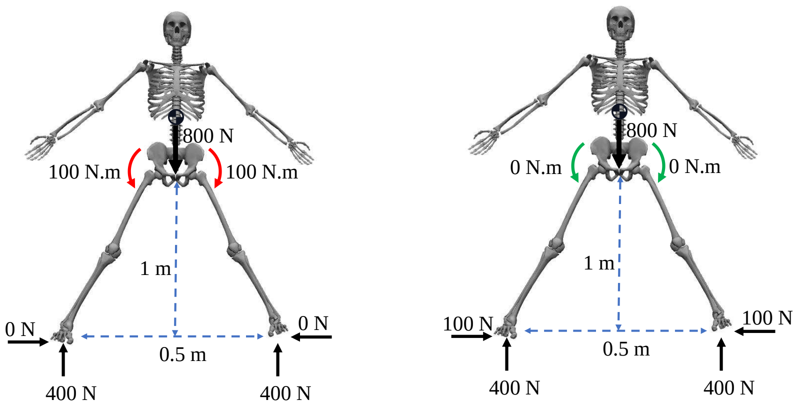
$$0 \leq F_y \tag{6}$$

$$\sqrt{F_x{}^2 + F_z{}^2} \leq \mu_s F_y \tag{7}$$

where μ_s is the static coefficient of friction between foot and the ground. Using the inequalities provided in Eqs. (3) to (7) written for both feet along with the joint torque limits $\boldsymbol{\tau}_{\min} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{\max}$, the GRF&Ms for both feet and joint torques can be estimated by minimizing the following second-order quadratic optimization problem subjected to the dynamic model, given in Eq. (1):

$$\min_{\boldsymbol{\tau}, \boldsymbol{F}_G} \quad J\left(\boldsymbol{\tau}, \boldsymbol{F}_G\right) = \boldsymbol{F}_G{}^T \boldsymbol{S} \boldsymbol{F}_G + \sum_{i=1}^{23} \left(\frac{\tau_i}{\tau_{i,\max}} \right)^2 \tag{8}$$

where $\boldsymbol{S}$ can be any positive definite matrix. From simulation studies, we observed that selecting smaller weights for the GRF&Ms compared to the joint torques results in more realistic outcomes. To illustrate this point, as shown in Fig. 2, a simplified case of static wide-stance is studied. Depending on the weights used in Eq. (8), both cases shown in the figure are possible outcomes of the model. It is clear that the body is more relaxed in the second case where the hip joint torques are smaller.



(a) No lateral ground reaction force.
Hip joint must be active.

(b) Sufficient lateral ground reaction force.
Hip joint is relaxed.

Figure 2: Outcome of the optimization in Eq. (8) when: (a) The optimization weight for ground reaction force is much higher than the weights for joint torques. (b) The weights for joint torques is much higher than weight for ground reaction force.

References

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[2] Skals, S., Jung, M. K., Damsgaard, M., and Andersen, M. S., 2017, "Prediction of ground reaction forces and moments during sports-related movements," *Multibody system dynamics,* **39**(3), pp. 175–195.