An Inverse Dynamical Model for Slip Gait

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Abstract. A inverse dynamical model for slip gait developed by using Kane's method of dynamics is described in this paper. The modeling was based on two separate sub-systems: anti-slip and anti-fall. Both sub-systems were modeled as an open kinematic chain and formulated using the same equations, so that the whole slip and fall process could be simulated using the same equations by switching input data. In the simulation, only kinematic data need to be input to obtain the joint moments and horizontal ground reaction force in the whole slip and fall process. The kinematic input data were acquired from one health male subject who was asked to perform the normal and slip gait. The anthropometric data for each body segment in the skeletal model was calculated using the body height, weight and the national standards on inertia parameters regression equations. The kinematic and kinetic results from the simulation are discussed in the paper which are well consistent with the conclusions in previous studies .

Keywords: slip and fall, modeling, human gait; kinetics.

1 Introduction

Slip-related fall is an accident people often encounter during walking in daily life. Investigations have shown that it has become a major cause of serious injury or even death especially for elders. Most studies on slip-related fall events can be classified as either biomechanical or epidemiological. Biomechanical analyses are commonly used in the studies of the potential slip risk via ground reaction forces and the proactive and reactive reaction strategies.

Almost all previous studies in slip and fall are based on in vivo experiments, although the mathematical modeling has been widely used as a method to investigate the human gait [1]-[4]] There are always some limitations in the in vivo experiments of slip gait. The most noticeable one is that there are no "real" falls occurring, because the protect equipments are employed and the anticipants must be ensured being safe. Therefore, a mathematical model for slip gait is urgently required. But up to now there has not been any mathematical model for slip gait reported yet. The complexity of the slip and fall procedure increases the difficulties in modeling the slip gait. Thus, the aim of this paper is to present a preliminary mathematical model of slip gait which was based on Kane's method for dynamical systems.

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2 Methods

Skeletal modeling. The human body model consists of 7 segments representing the stance foot, stance shank, stance thigh, swing shank, swing thigh, pelvis and HAT (head and torso). The number of segments was determined on the consideration of compromise between unnecessary complexity and adequate movement simulating. These segments are separated by anatomic points, which are the bottom of foot (BOF), the lateral center of malleoli (LCM), the lateral condyle of the femurs (LCF), the greater trochanter of the femurs (GTF), the xiphoid process (XIP) and the vertex (VER). The both arms and the swing foot is neglected in this model. As a preliminary attempt, all segments are assumed to be rigid and their motions are modeled in the sagittal plane only. And all segments are assumed to be connected by hinge joints. Furthermore, it has been demonstrated in the previous papers of our lab [5] that the slip and fall procedure can be divided into two steps: anti-slip and anti-fall. So that, the whole slip and fall procedure was modeled by two separate sub-systems. Moreover, in order to reduce the complexity of the model, the posterior foot was released completely during the anti-slip sub-system; while the anterior foot was released completely during the anti-fall sub-system. And the relative motion between the support foot and the ground is assumed as translation only in the sagittal plane. In this way, the ground was treated as a segment with zero velocity and infinite mass, which makes it possible to calculate the ground reaction forces (GRF) in the same way as the joint forces.

Experimental acquisition of gait data. To obtain the necessary kinematical data for the dynamic model, a normal healthy subject (male, 24 yr, 69.5 kg, 1.74m) underwent gait analysis during both level walking and slip gait. Some anatomical dimensions of this subject were measured to define the segments model. The subject did not have a prior history of lower extremity infirmity of musculoskeletal diseases that may affect the ability to perform the experiment at the time of testing.

Depending on the total body height and weight, the mass, the position of the center of mass in the local frame and the moment of inertia are determined with the regression equations of the national standards on the inertia parameters of adult human body [6]. And in order to adapt the model in this study, some corrections have been performed. The anthropometric data for each segment are listed in **Table 1**.

The subject wore shorts and walked on bare feet. He was required to walk at a self-selected comfortable pace along a 5 m plastic walkway, and to perform walking trials on dry and oily conditions respectively. In oily condition, the motor oil (40#) was evenly applied across 2 m long in the middle of the walkway. Thus, the from-dry-to-slippery condition under which falls usually occurred could be simulated in laboratory. The subject had a priori knowledge of the surface condition, whereas he was asked to walk as naturally as possible.

In order to record the movement of body segments, reflective markers were placed on the subject's sides: over the 5th metatarsal bone heads, the lateral center of malleoli, the lateral condyle of the femurs, the greater trochanter of the femurs, the anterior superior iliac spine, and the acromion of shoulders. Qualisys Motion Capture System (Qualisys Medical AB, Sweden) was employed to record the three-dimensional movements of the whole body at 200 Hz.

Table 1. The anthropometric data for each segment of the skeletal model. Mass center positions are from the proximal endpoint and the moments of inertia are in the sagittal plane.

Segment	Proximal endpoint	Distal End point	Segment length (*mm*)	Mass (*kg*)	Mass center position (*mm*)	Moment of inertia ($kg \cdot cm^2$)
Foot	BOF	LCM	61.5	0.9200	38.9600	ignored
Shank	LCM	LCF	371.7	3.0575	192.245	256.849
Thigh	LCF	GTF	514.1	9.7750	264.835	1572.415
Pelvis	GTF	XIP	461.0	18.2990	277.590	3733.031
HAT	XIO	VER	485.5	18.8875	201.105	4727.862

Governing Equations. The definitions of coordinate system and generalized coordinates in both anti-slip and anti-fall subsystems is shown in Fag.1. By applying Kane method, the governing equations are as

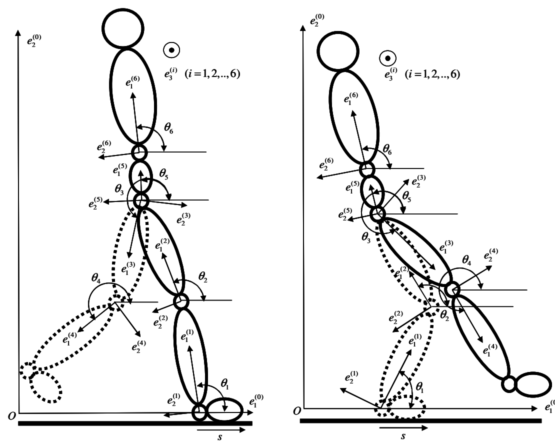


Fig. 1. The definitions of coordinate system and generalized coordinates in both anti-slip and anti-fall subsystems: (a) anti-slip; (

$$F^{(j)} + F^{*(j)} = 0 \quad (j = 1,2,..,7) \tag{1}$$

$$F^{*(j)} = \sum_{i=1}^{n} (\vec{R}_i^* \cdot \vec{v}_i^{(j)} + \vec{L}_i^* \cdot \vec{\omega}_i^{(j)}) \qquad (j = 1,2,..,7;\ \ n = 7) \tag{2}$$

$$F^{(j)} = \sum_{i=1}^{n} (\vec{R}_i \cdot \vec{v}_i^{(j)} + \vec{L}_i \cdot \vec{\omega}_i^{(j)}) \qquad (j = 1,2,..,7;\ \ n = 7) \tag{3}$$

Where $F^{*(j)}$ is the generalized inertia force , $F^{(j)}$ is the generalized applied force, $\vec{R}_i^*$ is the inertia force applied on the ith body segment, $\vec{L}_i^*$ is the inertia moment applied on the ith body segment, $\vec{R}_i$ is the active force applied on the ith body segment, $\vec{L}_i$ is the active torque applied on the ith body segment, ω and v are the partial angular velocities and partial velocities.

3 Results

The kinematic data in both subsystems during a slip gait were calculated and imported into the inverse dynamic model, respectively. The joint moments were obtained and normalized by the whole body weight of the subject. As a representative, the ankle joint moments and hip joint moments are shown in Fig.2 and Fig.3 respectively. Because the slip happened to the anterior right side, the anti-slip moments of right ankle are obviously increased until the posterior left leg supported the body. The posterior ankle moments are significantly large during the anti-fall period. The moments of hip joint on both sides indicate that the right hip joint moments were increased significantly during both anti-slip and anti-fall stage, while the posterior hip joint pays an important role in anti-fall stage.

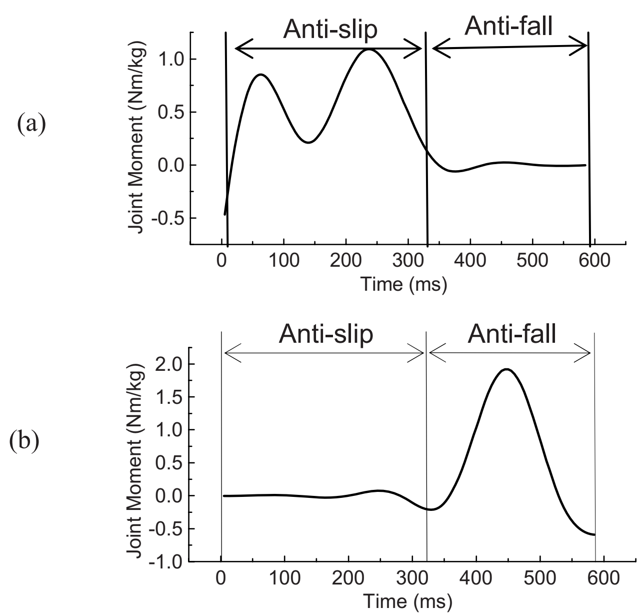
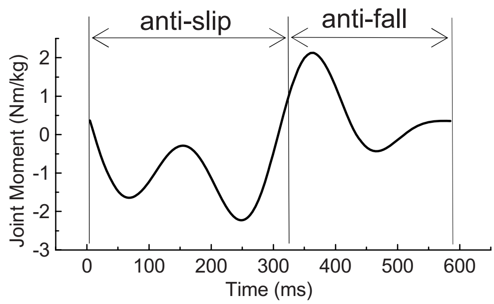


Fig. 2. The predicted ankle joint moments (a) right ankle joint; (b) left ankle joint

(a)



(b)

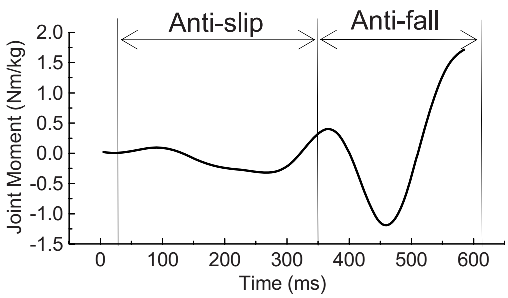


Fig. 3. The predicted hip joint moments (a) right hip joint; (b) left hip joint

4 Discussion and Conclusion

The objective of this paper was to define a mathematical model for slip gait. Since the procedure of a slip-related fall event is always complex, there is not any reported mathematical model of whole body for slip gait yet. Based on the theory of that the human reaction in slip-related fall events can be decomposed in anti-slip and anti-fall sub-procedures, the mathematical model was developed in this paper using two single support models. The governing equations of these two single support models were formulated in the same format. The joint moments and horizontal GRF in both procedures could be calculated only by switching the kinematic inputs.

The governing equations were obtained by applying Kane's dynamic method to avoid using the GRF as model inputs. In conventional applications of inverse dynamics in human gait analysis, the GRF are usually measured using force plates, which are planted in the walkway, and are inputs to the calculations [7]. But in the slip gait experiment, it is impossible to make the subject's feet to step on the force plates affirmatively in the sudden reaction. Even though the feet step on the force plates luckily, they usually slide out of the area of the force plates as well. Thus, it is very difficult to record the GRF during slip gait. Under such a circumstance, the application of inverse dynamics in this study employs the measured motions of all the major body segments as the only input data. And based on these kinematic data only, the joint moments and GRFs are predicted using by using this simulation.

The previous studies have reported that the ankle joint is very sensitive to the slip gait. The hip joint plays the most important role to maintain balance in healthy persons' unexpected slips [8]. The results from the presented procedure are consistent with these conclusions. Moreover, during the anti-fall procedure, the significantly increased joint moments of the posterior leg were consistent with the surface electromyography analysis on muscle reaction in slip-related falls [5].

It could be concluded that the inverse dynamic model established in this paper is an effective way for dynamic analysis of the human body in slip gait.

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