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Short communication

Effects of foot modelling on the human ankle kinematics and dynamics

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ABSTRACT

In this study, effects of some of the foot modelling assumptions on the ankle kinematics and dynamics are investigated based on the experimental data. For the kinematics analysis, the appropriateness of the stationary axis of rotation of the human ankle flexion is examined. Moreover, an interpolated function which is capable of predicting the directional changes of this axis is proposed. For the dynamics analysis, two main modelling assumptions of the number of the foot segments and the dimension of the foot model are the subject of the study. To this end, the ankle joint torque and power are selected as the comparison indicators and inverse dynamics analyses are carried out. The analyses show that the number of segments of the foot model does not have a considerable effect on the calculated ankle joint torque. On the other hand, the calculated ankle power is highly affected by both of the segmentation and the dimension of the foot model.

1. Introduction

In the past years, different foot models for gait kinematics and dynamics studies have been introduced in the literature [6,12,18,20,23,25,27,30,31]. In most of these human gait analyses, ankle joint has been modelled based on a revolute joint [15,16,19,27], two revolute joints with non-orthogonal axes of rotations [7,9,24], or a spherical joint [26,30,31]. The popularity of modelling the ankle joint with the lower kinematics pairs is mainly due to their less-complex kinematic behaviour which makes them simpler to be implemented in the human gait simulations and analyses. On the other hand, the applicability and appropriateness of these ankle models for the specific applications of interest are not well validated. More rigorous ankle kinematics analyses reported that the instantaneous axis of rotation (IAR) of the foot with respect to the tibia does not have a fixed orientation and location during the ankle rotation, even in the cases of pure flexion, pronation/supination or internal/external rotation performances [21,22]. A mean orientation is usually selected when the ankle axis of rotation is modelled by a revolute joint.

Furthermore, on the foot modelling side, different models are proposed and used in the literature. Several studies have been done based on the point or circular shape foot models which cannot well capture the contact properties of the gait [12,14,28]. One-segment [5,31], two-segment [27,30], or three-segment foot models [6] are also proposed in the literature. Some studies suggested more segments for the foot [18,20,23,25], for instance, the eight-segment foot by MacWilliams et al. [18]. Most of the multi-segment foot models have been used for kinematics analysis of the foot. Very few investigations have been done on the foot dynamics. Using multi-segment foot models to capture kinematics of the gait requires enough attention and study to appropriately place markers on the foot. As foot inter-segment movements are mostly in a narrow range, the marker placement should be well studied in these models to avoid drastic measurement errors. Furthermore, as the motion of some segments cannot be directly captured,

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approximations are used which the result is error-prone. Although the human gait can be simulated using the introduced models, still more improved models are needed as many simulations are for single step and not multiple step gait cycles [2,15]. This drawback can be due to the fact that, in some situations, existing models may predict unrealistic foot kinematics and dynamics. Furthermore, although the three-dimensional multi-segment human model, as the most complex model, exists, a simple foot model consisting of one segment is mostly used for dynamics analysis [19,31]. This might not fully characterize different phenomena in the human walking.

Foot models are mainly developed based on the following three assumptions: type of the ankle joint, number of segments, and dimension of the model. Conclusions have been drawn using these models while not enough justifications on the appropriateness of the utilized models were usually provided. Sensitivity of the predicted behaviours of these foot models with respect to each of the assumptions has not been completely understood. In the current paper, the aim is to further study the foot models which are widely used in the literature for certain kinematics and dynamics analyses. To this end, for the ankle joint kinematics, the leg–foot flexion motion is further analyzed in order to better understand the complex behaviour of the ankle during the gait. The ankle flexion motion is studied as the gait is accomplished mostly by this mode of rotation. An interpolated function to characterize the IAR of the foot with respect to the tibia is proposed. This function can be easily personalized and used for any other subject under the study. For dynamics studies, an inverse dynamics analysis is performed by calculating the ankle joint torque and power, as two comparison indicators. Comparison between the predicted results by these models are carried out. This can better demonstrate the differences in the predicted dynamics when different assumptions are made for foot modelling. Furthermore, by the aid of these analyses, more insight into drawbacks of these models and the appropriateness of them for different applications in the gait analysis can be gained.

2. Kinematics and dynamics formulation

Different methods to calculate the direction of the Instantaneous Axis of Rotation (IAR) which is in the same direction as the angular velocity of a rigid body exist in the literature. In this study, the angular velocity of a rigid body is calculated based on positions and velocities of three non-collinear points of the body, denoted by $\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3$ and $\dot{\mathbf{p}}_1, \dot{\mathbf{p}}_2, \dot{\mathbf{p}}_3$, respectively. These positions and velocities are stored in matrices as $\mathbf{P} = [\mathbf{p}_1 - \mathbf{c} \quad \mathbf{p}_2 - \mathbf{c} \quad \mathbf{p}_3 - \mathbf{c}]$ and $\mathbf{P} = [\dot{\mathbf{p}}_1 - \dot{\mathbf{c}} \quad \dot{\mathbf{p}}_2 - \dot{\mathbf{c}} \quad \dot{\mathbf{p}}_3 - \dot{\mathbf{c}}]$, where $\mathbf{c} = \frac{1}{3}\sum_{i=1}^{3} p_i$ and $\dot{\mathbf{c}} = \frac{1}{3}\sum_{i=1}^{3} \dot{\boldsymbol{p}}_i$. Now, if we define $\mathbf{R} = \mathbf{P}\mathbf{P}^T$, and $\mathbf{J} = tr(\mathbf{R})\mathbf{E} - \mathbf{R}$, where $\mathbf{E}$ is the identity matrix, *tr* and *vect* are the trace and vector operators respectively, the angular velocity of the body can be expressed as [3]

$$\boldsymbol{\omega} = 2\mathbf{J}^{-1}\mathrm{vect}(\dot{\mathbf{P}}\mathbf{P}^T). \tag{1}$$

The ankle joint torque and power are common indicators in the human gait dynamics analysis [8,11]. For a one-segment foot model, based on the application of the angular momentum theorem on the foot segment, the ankle joint torque can be formulated as

$$\mathbf{T}_a + \mathbf{T}_r + \mathbf{r}_{ca} \times \mathbf{F}_a = \mathbf{I}\,\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) \tag{2}$$

where $\mathbf{T}_a$ is the ankle torque, $\mathbf{T}_r$ is the resultant ground reaction moment at the centre of mass of the segment, $\mathbf{r}_{ca}$ is the position vector from the centre of mass to the ankle position, $\mathbf{F}_a$ is the ankle joint force, $\mathbf{I}$ is the foot tensor of inertia at the centre of mass and $\boldsymbol{\omega}$ is the angular velocity vector of the foot segment. If the foot–ground contact interaction is measured through force plates, as is the usual case in inverse dynamics studies, the resultant ground reaction moment can be expressed as

$$\mathbf{T}_r = \mathbf{T}_f + \mathbf{r}_{cf} \times \mathbf{F}_f \tag{3}$$

where $\mathbf{T}_f$ is the ground reaction moment with respect to the centre of the force plate, $\mathbf{r}_{cf}$ is the position vector from the centre of mass to the centre of the force plate and $\mathbf{F}_f$ is the foot–ground contact force. The formulation can be extended for the two-segment foot as

$$\mathbf{T}_a + \mathbf{T}_r + \mathbf{r}_{c_1a} \times \mathbf{F}_a + \mathbf{r}_{c_1m} \times \mathbf{F}_m - \mathbf{r}_{c_2m} \times \mathbf{F}_m = \mathbf{I}_1\dot{\boldsymbol{\omega}}_1 + \boldsymbol{\omega}_1 \times (\mathbf{I}_1\boldsymbol{\omega}_1) + \mathbf{I}_2\dot{\boldsymbol{\omega}}_2 + \boldsymbol{\omega}_2 \times (\mathbf{I}_2\boldsymbol{\omega}_2) \tag{4}$$

where $\mathbf{r}_{c_1a}$ is the position vector from the centre of mass of the hindfoot (segment 1) to the ankle position, $\mathbf{r}_{c_1m}$ is the position vector from the centre of mass of the first foot segment to the metatarsal position, $\mathbf{F}_m$ is the metatarsal reaction force, $\mathbf{r}_{c_2m}$ is the position vector from the centre of mass of the forefoot (segment 2) to the metatarsal position, $\boldsymbol{\omega}_\mathrm{i}$ is the vector of angular velocity of the *i*th foot segment, and $\mathbf{I}_i$ is the moment of inertia of the *i*th foot segment respectively. Due to low inertial effects of the forefoot segment, the ground reaction forces are assumed to act on the hindfoot only. The ankle joint torque for foot models with more segments can be similarly derived as well. Power done by muscles acting on the ankle joint can be formulated as, $P = \mathbf{T}_a \cdot \boldsymbol{\omega}_{rel}$, where $\boldsymbol{\omega}_{rel}$ is the relative angular velocity of the foot with respect to the tibia.