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TOWARDS AN EFFICIENT LARGE-SCALE PREDICTIVE MODEL OF HUMAN WALKING

[1]Dan Hu, [1]Lei Ren and [2]David Howard
[1]School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M60 1QD, UK
E-mail: lei.ren@manchester.ac.uk
[2]School of Computing, Science and Engineering, University of Salford, Salford, M5 4WT, UK

SUMMARY

This paper presented our current progress towards the development of a novel large-scale predictive model to simulate human walking by combining inverse dynamics method and numerical optimization techniques. The proposed predictive walking model requires minimal measurement inputs and only two simple gait descriptors (walking speed and stride length) are needed to generate 3D gait kinematics and kinetics over a complete gait cycle. The inverse dynamic method is used here due to its high computational efficiency and intrinsic compatibility with the constraints defining the human walking motion. In this study, quaternions are used to represent the spatial rotations of anatomical joints, which would avoid the singularity problem and also increase the computational efficiency. The 3D gait measurement data, including joint motions, joint moments and ground reaction forces will be used to validate the model. A fully validated predictive walking model would find many potential applications in clinical motion analysis, rehabilitation engineering, surgical planning etc.

INTRODUCTION

Walking is a motor task with high degree of complexity, organization and efficiency. A large number of studies have been carried out to investigate the biomechanics of human walking in the past decades. Three-dimensional motion analysis technique has been used to record the fine details of the human walking gait, including the segmental and joint motions, ground reaction forces and electromyographic activities [1]. Furthermore, the internal kinetic variables contributing to walking which are hard to be measured in-vivo directly, have also been estimated using modeling techniques, for example, the muscle forces and the torques produced by the muscles around joints [2,3]. However, the majority of the outcomes have been descriptive in nature as they are based on measurements, which by its very nature tells us what happens but not why it happens. Very few studies have been conducted to predict human walking [4,5,6] (i.e. not based on measurements), which has the potential of explaining the reasons for particular model behaviors. Furthermore, only predictive modeling can be used for the virtual prototyping of devices that interact with the body during walking. Therefore a novel predictive model based on inverse dynamics and optimization approach for simulating 3D human walking is proposed. Some preliminary results during model construction have been presented.

METHODS

The human body was modeled as an articulated multi-body system (see Figure 1) with 13 segments (head, torso, pelvis, upper arms, forearms, thighs, shanks and feet) and 25 degree of freedoms (DoFs). The 3D dynamics of the human body is determined using the following equations

$$m\ddot{\vec{p}}_{cm} = m\vec{g} + \vec{F}_{gl} + \vec{F}_{gr} \qquad (1)$$

$$\dot{\vec{H}}_{cm} = \vec{M}_{cm} \qquad (2)$$

$$\vec{H}_{cm} = \sum_{i=1}^{n}[(\vec{p}_{ci} - \vec{p}_{cm}) \times m_i \cdot (\vec{v}_{ci} - \vec{v}_{cm}) + I_{ci} \cdot \vec{\omega}_{ci}] \qquad (3)$$

$$\vec{M}_{cm} = \vec{M}_{gl} + \vec{M}_{gr} + (\vec{p}_{gl} - \vec{p}_{cm}) \times \vec{F}_{gl} + (\vec{p}_{gr} - \vec{p}_{cm}) \times \vec{F}_{gr} \qquad (4)$$

where $\vec{p}_{cm}$ is the position vector of the instantaneous center of mass (CoM) of the body, and $\vec{p}_{ci}$ is the CoM position of the i^{th} segment. $\vec{F}_{gl}$ and $\vec{F}_{gr}$ are the ground reaction forces on the left and right foot, respectively. In Equation (2), the change rate of the angular momentum about the CoM $\dot{\vec{H}}_{cm}$ equals the resultant external moment $\vec{M}_{cm}$. Here $\vec{p}_{gl}$ and $\vec{p}_{gr}$ in Equation (3) are the position vector of the centre of pressure (CoP) on left and right foot respectively, and $\vec{M}_{gl}$ and $\vec{M}_{gr}$ are the ground reaction moments on left and right foot, respectively.

Figure 1: The 3D whole body multi-segment model with 13 segments and 25 DoFs

Therefore, the dynamics of the i^{th} body segment can be determined one by one starting from the contact foot using the following equations

$$m_i \ddot{\vec{p}}_{ci} = m_i \vec{g} + \sum_{k=1}^{n_{ji}} \vec{F}_{jk}^{(i)} + \sum_{k=1}^{n_{ei}} \vec{F}_{ek}^{(i)} \quad (5)$$

$$I_{ci} \cdot \vec{\alpha}_i + \vec{\omega}_i \times (I_{ci} \cdot \vec{\omega}_i) = \sum_{k=1}^{n_{ji}} \vec{M}_{jk}^{(i)} + \sum_{k=1}^{n_{ei}} \vec{M}_{ek}^{(i)} + \sum_{k=1}^{n_{ji}} (\vec{r}_{jk}^{(i)} \times \vec{F}_{jk}^{(i)}) + \sum_{k=1}^{n_{ei}} (\vec{r}_{ek}^{(i)} \times \vec{F}_{ek}^{(i)}) \quad (6)$$

Here $\vec{F}_{jk}^{(i)}$ and $\vec{F}_{ek}^{(i)}$ are the k^{th} joint force and external force vector acting on the i^{th} segment respectively. Also $\vec{M}_{jk}^{(i)}$ and $\vec{M}_{ek}^{(i)}$ are the k^{th} net muscle moment and external moment acting on the i^{th} segment. I_{ci} is the inertial tensor around the mass center of the i^{th} segment, ω_i and α_i are the angular velocity and acceleration vectors of the i^{th} segment.

In kinematic representation, the quaternions were used to describe the spatial rotation of each joint, which reduced the variables from nine in the rotation matrix to only four and also avoided the singularity problem. For the unit quaternion Λ,

$$\Lambda = [\lambda_0, \lambda_1, \lambda_2, \lambda_3] = [\lambda_0 = \cos(\theta/2), \lambda_i = \sin(\theta/2) u_i] \quad (7)$$

where $u = [u_1, u_2, u_3]$ is the unit vector, and θ is the rotation about the vector. The angular velocity and acceleration can be expressed as

$$\omega = 2L\dot{\Lambda} \quad (8)$$

$$\dot{\omega} = 2L\ddot{\Lambda} \quad (9)$$

$$L = [-\lambda_1, \lambda_0, \lambda_3, -\lambda_2; -\lambda_2, -\lambda_3, \lambda_0, \lambda_1; -\lambda_3, \lambda_2, -\lambda_1, \lambda_0] \quad (10)$$

The stance foot was modeled as a rigid body with a curved plantar surface rolling on the ground without slipping. Thereby the foot kinematic during stance phase can be described as

$$\Delta x = f(\Lambda_{ft}) \quad (11)$$

$$y = g(\Lambda_{ft}) \quad (12)$$

$$\Delta z = h(\Lambda_{ft}) \quad (13)$$

where Λ_{ft} represents the foot rotation with respect to the ground surface.

Due to the cyclical feature of the walking motion, the quaternion element for each joint is represented using a set of finite Fourier series

$$\lambda_i = a_0^{(i)} + \sum_{k=1}^{n} (a_k^{(i)} \cos(k\omega t) + b_k^{(i)} \sin(k\omega t)) \quad (14)$$

The Fourier coefficients for each quaternion element will be determined by minimizing the energy cost whilst subjected to a set of constraints defining the human walking.

RESULTS AND DISCUSSION

Three-dimensional gait measurement for the whole body walking of a male subject (age: 25; weight: 68.8kg; height: 177cm) has been conducted using a multiple infrared camera system and a set of force plates. To verify the constructed whole body multi-segment before the optimization, all the joint quaternion values derived from the measurement data were used as inputs to the inverse dynamics model. The calculated vertical ground force was compared with recorded force plate data (see Figure 2). Although the typical two-humped pattern was generated by the model, there is still some discrepancy between the simulated result and measurement data, which needs further improvement on the model construction.

In addition to the computational efficiency, the use of quaternions in kinematic representation can bring some benefits to the final optimization scheme, e.g. it can constrain all the optimization parameters within a range of $[-1,1]$. For future optimization simulations, only the energy cost performance objective may not be sufficient. A multi-objective optimization scheme involving both energy expenditure and body stability will be used in future studies.

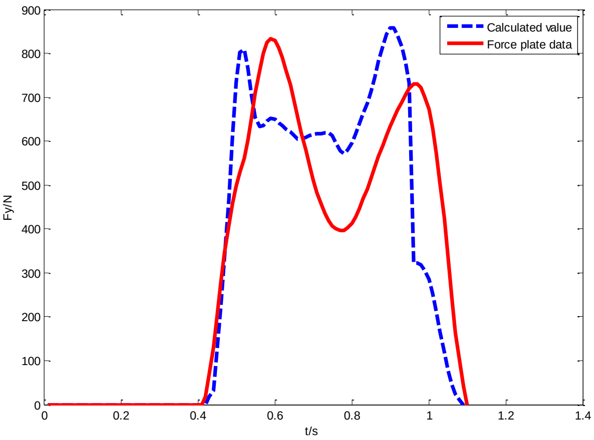

Figure 2: The calculated vertical ground reaction force compared with the recorded force plate data

CONCLUSIONS

A computational framework based on a large-scale whole-body human model to predict human walking is proposed. Quaternions were used to define the spatial rotations of joints, and inverse dynamics method instead of forward dynamics is used to evaluate the joint kinetics and energy cost during walking. A multi-objective optimization scheme involving both energy cost and body stability will be used in the future to predict walking kinematics and kinetics with minimal measurement inputs.

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REFERENCES

1. Cappozzo A, et al., *Gait Posture*, **21**: 186-196, 2005.
2. Erdemir A, et al., *Clin Biomech*, **22**: 131-154, 2007.
3. Delp SL, et al., *IEEE Trans. Biomed. Eng.* **55**, 1940-1950, 2007.
4. Anderson FC, Pandy MG., *J. Biomech. Eng.* **123**, 381–390, 2001
5. Ren L, et al., *J Biomech*, **40**: 1567-1574, 2007.
6. Kim HJ et al., *J Biomech Eng*, **130**, 031002, 2008