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A New Methodology for Three-dimensional Dynamic Analysis of Whole Body Movements

Yanxin Zhang[1 +] and Simon M. Hsiang[2]

[1] School of Sport Science, Exercise, and Health The University of Western Australia Crawley, WA 6009
[2] Edward P. Fitts Department of Industrial Engineering, North Carolina State University, Raleigh, NC 27695-7906

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Abstract. With the development of modern motion analysis technologies, biomechanical analysis of human activities can be evaluated by motion camera system with relatively simple set of external reflective markers. In this study a three-dimensional (3D) marker-based whole body biomechanical model was developed to evaluate whole body activities. This model can be used with motion analysis system to provide mathematical description of the kinematics of body segments and conduct kinetic analysis. As an application, this model has been used to compute the lower back torque during manual asymmetric lifting activities.

Keywords: biomechanical model, motion analysis.

1. Introduction

Since first introduced for gait analysis ([1], [3], [4], [6], [7], [8]), motion analysis techniques have been extended during the past two decades to investigate many human activities. Currently, research in sports biomechanics, postural balance studies, clinical assessment of functional capacity, and ergonomics are all being studied using motion analysis systems and the new techniques are still under development. Technically, motion analysis systems use light-weight, unobtrusive passive or active skin-attached markers to record unconstrained 3D kinematics of body segments, which are usually represented by a kinematic chain. Based on the kinematics data, a suitable biomechanical model is created from the positions of non-collinear markers affixed to each body segment. Then the joint angles, joint forces and mechanical moments (torques) imposed are estimated by inverse dynamic biomechanical computations. The number of markers used and their arrangements are dependent on the objectives of study and different 3D rigid segment models have been proposed ([1], [3], [4], [6], [7], [8], [9]). To date, most of the proposed 3D rigid segment models are functional lower body or upper body models with their major usage for clinical research. However, the whole body biomechanical modeling methods, which are very useful in sports science to evaluate the whole body movements, are very limited ([5], [13]) and usually require complex calibration procedures to set up the marker and formulate an anatomical axis system. Due to these limitations, these methods are more suitable for lab data collection than in situ survey and investigation.

With the development of modern technology of motion analysis system, measurement accuracy has been drastically improved. New method can be expected by using relatively simple set of external markers developed for time-efficient kinematic analysis of human movements in a more standardized approach. The aim of this study is to develop a new biomechanical model to analyze three-dimensional dynamics during whole body movements, which includes (1) a three-dimensional whole body kinematic model based on proposed standards of International Society of Biomechanics (ISB) ([10], [11]) and (2) kinetic analysis based on the kinematic model.

2. Method

From a biomechanical point of view, the whole human body can be divided into separate rigid segments. The position and orientation of each segment can be recorded by motion analysis system with external

[+] Corresponding author. Tel.: +61-8-6488-2608; fax: +61-8-6488-1039.
E-mail address: yanzhang@cyllene.uwa.edu.au

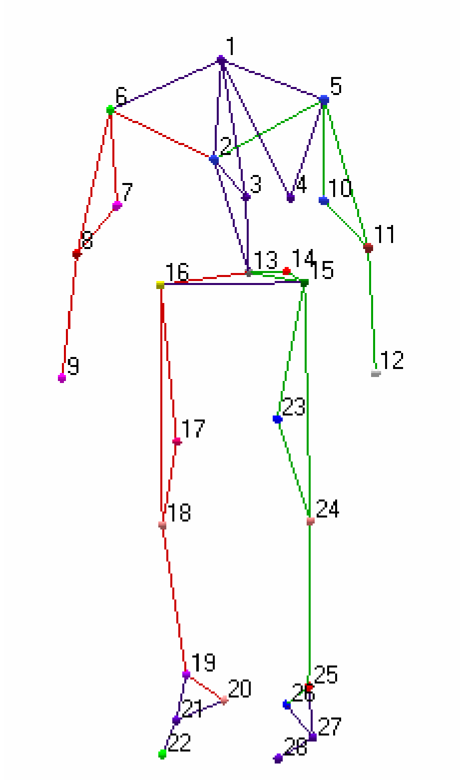
markers mounted on the surface of landmark's position of the body. Consequently, mathematical description of the rigid body segment can be set up based on the marker positions and further kinetic analysis can be conducted. Specifically, proposed method includes a three-step modeling approach: (1) definition of joint coordination system in the anatomical position using non-collinear markers affixed to each rigid body segment; (2) calculation of joint angles based on the defined joint coordinate systems; and (3) three dimensional kinetic analysis. These are described in detail in the next sections.

2.1. Definition of joint coordination system

The biomechanical model include twelve rigid segments: left and right feet, left and right lower legs, left and right upper legs, upper and lower torso, left and right upper arms, and left and right lower arms. Major joints included in the model are the following: left and right elbows, left and right shoulders, left and right knees, left and right hips, left and right ankles, thorax and pelvis. To represent motion of each segment, it needs to determine the instantaneous orientation and position of orthogonal sets of axes that are embedded in the rigid bony segments of the body. This determination involves the definition of specific sets of segment coordinate systems. These will include a reference segment coordinate system which provides a reference for segment location in space, and a referred coordinate system which are created from the position of at least three non-collinear markers affixed to each rigid body segment. By using the segment coordinate system it is possible to determine the relative positions of two adjacent body segments. For example, the rotation of the elbow joint can be determined on the basis of the relative rotation from forearm coordinate system to the upper arm coordinate system.

In this model, totally 28 markers were used to represent the whole human body, as shown in Fig. 1. These markers were mounted on the lateral aspects of each major segment to give the greatest visibility from views by motion cameras. Based on all markers' positions, the bony landmarks of the major joints can be determined. The left and right hip joint centers (HJC) were determined by a regression equation ([1]) and specified in the pelvis' local coordinate system. The left and right knee joint centers (KJC) were defined by the HJCs, the thigh markers and the knee markers. The shoulder joint centers were determined by the "shoulder" marker positions and the elbow centers were determined by the "elbow" marker positions. Based on all markers' positions, the joint coordinate systems were defined in table 1 which is in accordance with the proposed standards of ISB ([10], [11]).

For each body segment a Cartesian coordinate system was established. The axes in these coordinate systems were defined based on bony landmarks. The common origin of both coordinate systems is the point of reference for the linear translation occurring in the joint.



No.	Name	No.	Name
1	C7	15	Left Hip
2	Sternum	16	Right Hip
3	Mid Back	17	Right Thigh
4	Left Scapula	18	Right Knee
5	Left Shoulder	19	Right Ankle
6	Right Shoulder	20	Right Heel
7	Right Bicep	21	Right Mid Foot
8	Right Elbow	22	Right Toe
9	Right Wrist	23	Left Thigh
10	Left Bicep	24	Left Knee
11	Left Elbow	25	Left Ankle
12	Left Wrist	26	Left Heel
13	L5_S1	27	Left Mid Foot
14	Left Pelvis	28	Left Toe

j **Fig. 1:** Biomechanical representations human body er modelfential equationsodethod you used to remnt and 28 markers' positions shown in Eva^{TM} software 9

Table1. Joint coordinate systems defined by marks's positions

Segment Name	Joint Coordinate System Description
Thorax	Y: Defined by the direction from Mid back to C7, X: perpendicular to the saggital plane defined by Sternum-C7- Mid back, pointing laterally, Z: as defined by X and Y
Pelvis	Y: Defined by the direction from L5_S1 to Mid back, X: perpendicular to the saggital plane defined by Sternum-L5_S1- Mid back, pointing laterally, Z: as defined by X and Y
Right Upper Arm	Y: longitudinal direction from right Shoulder to right Elbow X: normal vector pointing medially to the plane formed by right Shoulder-Elbow-Bicep, pointing laterally Z: as defined by X and Y

Table1. (continue)

Right Lower Arm	Y: longitudinal direction from right Elbow to right Wrist X: normal vector pointing medially to the plane formed by right Shoulder-Elbow-Wrist, pointing laterally Z: as defined by X and Y
Right Thigh	Y: longitudinal direction from right KJC to right HJC X: normal vector pointing medially to the plane formed by right Knee-Hip-Thigh, pointing laterally Z: as defined by X and Y
Right Lower Leg	Y: longitudinal direction from right Ankle to right KJC X: normal vector pointing medially to the plane formed by right Knee-Hip- Ankle, pointing laterally Z: as defined by X and Y
Right Foot	Y: longitudinal direction from right Heel to right Toe X: normal vector pointing medially to the plane formed by right Heel-Toe-Ankle, pointing laterally Z: as defined by X and Y
Left Upper Arm	Y: longitudinal direction from left Shoulder to left Elbow X: normal vector pointing medially to the plane formed by left Shoulder-Elbow-Bicep, pointing laterally Z: as defined by X and Y
Left Lower Arm	Y: longitudinal direction from left Elbow to left Wrist X: normal vector pointing medially to the plane formed by left Shoulder-Elbow-Wrist, pointing laterally Z: as defined by X and Y
Left Thigh	Y: longitudinal direction from left KJC to left HJC X: normal vector pointing medially to the plane formed by left Knee-Hip-Thigh, pointing laterally

	Z: as defined by X and Y
Left Lower Leg	Y: longitudinal direction from left Ankle to left KJC X: normal vector pointing medially to the plane formed by left Knee-Hip-Ankle, pointing laterally Z: as defined by X and Y
Left Foot	Y: longitudinal direction from left Heel to left Toe X: normal vector pointing medially to the plane formed by left Heel-Toe-Ankle, pointing laterally Z: as defined by X and Y

2.2. Calculation of joint angles

Once the joint coordinate systems are defined, then in each time frame the coordinates of the referred segment with respect to the reference segment can be represented by a rotation matrix *R*. This matrix is equivalent to the composition of a sequence of three rotations delineated by three Euler angles α, β and γ, with the first rotation starting form the reference coordinate system. If a segment rotates first about the x-axis, then the y-axis, and finally the z-axis, such a sequence of rotations can be represented as the matrix product.

$$R(\alpha,\beta,\gamma)=\begin{pmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{pmatrix}=R_x(\alpha)*R_y(\beta)*R_z(\gamma)$$
$$=\begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}*\begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}*\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{pmatrix}$$
$$=\begin{pmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma-\sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma-\sin\alpha\sin\gamma \\ \sin\alpha\sin\beta & \sin\alpha\sin\beta\sin\gamma-\cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma-\cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \sin\beta\cos\gamma \end{pmatrix} \tag{1}$$

Where α, β, γ are the rotation angles about the x, y, and z axis respectively. Given a rotation matrix *R*, we can compute the Euler angles by equating each element in R with the corresponding element in the matrix product.

$$\begin{aligned} \beta &= \mathrm{Atan2}(-r31,\sqrt{r11^2+r21^2}) \\ \alpha &= \mathrm{Atan2}(r21/\cos\beta, r11/\cos\beta) \\ \gamma &= \mathrm{Atan2}(r32/\cos\beta, r33/\cos\beta) \end{aligned} \tag{2}$$

Since matrix multiplication does not commute, the order of the axes that one rotates about will affect the result. In this paper, it is defined that each segment rotates in an order which is consistent with the ISB recommendations standard ([10], [11]).

2.3. Kinetics analysis

An inverse dynamic analysis procedure was used to calculate the reactive forces and torques at all intersegmental joint. In this procedure, each body segment is considered as a rigid body. The body segments are thought to be interconnected as a kinematic chain. Given subject's height and weight, the inertial property of the segments, and length of the segments can be calculated using standard biomechanical procedures ([2]). Application of the Newton's equations of motion to the segment system gives

$$\sum_i F_i = F_D + F_p + W = \dot{P} \tag{3}$$

and

$$\sum_i T_i = T_p + T_D + L_D \times F_D + W \times d_i = \dot{H} \tag{4}$$

where P is the momentum of the segment, H is the angular momentum of the segment, F_D and T_D are the force and torque from the distal joint, F_P and T_P are the force and torque from the proximal joint, L_D is segment length, d_i is the length from CG to the proximal joint, W is the gravity. Equation 3 and 4 basically says that the sum of all the external forces acting on the system is the same to the rate of change in the momentum of the system and the sum of all the external torques acting on the system is equal to the rate of change in the angular momentum of the system, respectively. Rates of change in the linear and angular momentums can be computed from the motion analysis data.

Rearranging equation 3 and 4 yields:

$$F_p = \dot{P} - F_D - W \tag{5}$$

$$T_p = \dot{H} - T_D - L_D \times F_D - W \times d_i \tag{6}$$

where

$$\dot{P} = ma$$

$$H = I \times w$$

$$\dot{H} = (H')_{rot} + w \times H \qquad (7),$$

I is the moment inertia of the segment, a is the acceleration, and w is the angular velocity. Equation 5 and 6 now have two groups of unknowns, F and T. Assuming that F_D and T_D are somehow known, one can solve the system for F_P and T_P. In order to solve equation 5 and 6 for F_P and T_P, F_D and T_D must be known. For most whole body activities, F_D and T_D for the lower arm are known as the external load. Based on this information, F_P and T_P of other segment can be computed following the sequence: lower arm, upper arm, torso, upper leg, and lower leg. The low back torques can be computed based on the posture and moment information by this process.

3. Application

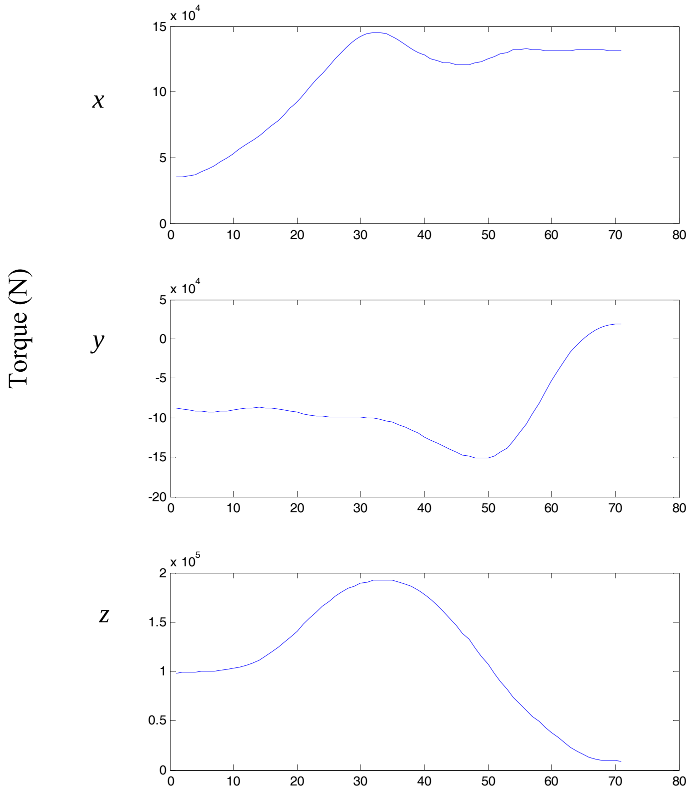


Fig. 2: Graphical representations of calculated lower back joint torque of a single subject during asymmetric lifting. The torque includes three vectors *x*, *y*, and *z*, which represents flexion/ extension, adduction/abduction and internal/external rotation respectively.

This method can be used in the kinematic and kinetic analysis of whole body activities that has large motion ranges. As an application and testing of this method in analyzing real kinematic data, an asymmetric manual lifting activity was investigated. This movement was selected based on the following reasons: (1) this type of activity involving with both upper and lower extremity motion (2) this activity generate large torso twisting motion power which is a big concern of injury and only 3-dimensinal model can reveal this, and (3)the testing results can be compared with other previous published results.

In our study, one male subject was tested to perform a series of asymmetric manual lifting tasks and the kinematic data were collected. Prior to data collection, the subject practiced the one-handed lifting activities from floor to knuckle height by lifting a container (10lbs). During data collection, lifts were performed which include trunk twisting at normal pace. For every lifting task, the subject was fitted with reflective markers which were placed on the wrists, elbows, shoulders, hips, knees, ankles, heels, mid-back, low-back, upper back and toes as shown in Figure 1. The markers' displacements versus time information were recorded by a three-dimensional motion analysis high-speed camera system. The high speed camera system consists of 5 high speed cameras located at different positions with the resolution of 60 frames a second, therefore all the trajectory path of the reflective markers can be recorded clearly. The marker position data recorded by the high speed digital cameras were filtered with the Butterworth filter using a 6 Hz cut-off frequency.

The lower back torque was computed based on the method illustrated in the previous section. Graphical representations of calculated lower back joint torques\ for one lifting trial are presented in Fig. 2. It is revealed that twist rotation of the lower back (the z-axis) made important contributions to the total net torque for asymmetric lifting with the maximal twisting torque happening at the middle stage of the lifting phase. The finding is in accordance with previous finding ([13]) which use Kingma's model ([5]) to compute the lower back torque. Our result shows that by using a comparably simple maker set, the joint kinetic parameters can also be accurately estimated.

4. Discussions

With the development of modern 3D measurement techniques (dynamic MRI, biplane radiography, electromagnetic tracking systems, and optical tracking systems etc.), human activities can now be investigated at multi-level stages based on the individual research purpose. Among these multiple choices, optical tracking systems are one of the best suitable tools for applications in sports science with the advantage of measurement accuracy and less constraints of the human movements. In order for a motion analysis system to provide kinematical data it must be used in conjunction with a suitable biomechanical model which should consider both time-efficiency and measurement accuracy.

In this study a new biomechanical model was developed to investigate human activities for this purpose. With the ability to accurately define the joint axes orientation in their anatomical position with minimal number of necessary reflective markers, this method can quantitatively improve assessment of complex manual tasks by conducting 3D dimensional kinematics and kinetic analysis for major joints. One major advantage of the method is that it can provide three-dimensional mathematical description of the kinematics of rigid body segments based on the proposed standards of ISB. Such an approach can lend itself to standardization of joint angles for the fostering of data sharing and comparisons with biomechanics communities. This model has been used in the kinetic analysis of asymmetric lifting tasks. The results showed that the methods can successfully represent the 3 dimensional characteristics of the low back torque. It is believed that the model can be used in the biomechanical analysis of a wide range of human movements. The model can also have the potential to incorporate with proposed functional methods [1] and optimization methods [12] to optimize the bony landmarks' positions and increase the estimation accuracy.

5. References

[1] T. F. Besier, D. L. Sturnieks, J. A. Alderson, and D. G. Lloyd. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics*. **36** (2003) 8: 1159-1168.

[2] D. B. Chaffin and G. B. J. Andersson. *Occupational Biomechanics*, 2nd Edition, John Wiley & Sons, New York. 1991

[3] M. E. Eastlack, J. Arvidson, L. Snyder-Mackler.. Interrater reliability of videotaped observational gait analysis assessments. *Physical Therapy*, **71**(1991): 465-472.

[4] M. P. Kadaba, H. K. Ramakrishnan, M. E. Wootten, J. Gainey, G. Gorton, GVB Cochran. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research*.

7(1989):849–860.

[5] I. Kingma, M. P. Looze, H. M Toussaint, J. G Klijnsma, and T. B. M. Bruijnen. (1996) Validation of a full body 3-D dynamic linked segment model. *Human Movement Science*. 15, 833-860.

[6] D. E. Krebs, J. E. Edelstein, and S. Fishman. Reliability of observational kinematic gait analysis. *Physical Therapy*. **65**(1985): 1027-1033.

[7] L. W. Lamoreux. Kinematic measurements in the study of human walking. *Bull Prosthet Res.* **10**(1971) 15:3-84.

[8] M. J. Peterson, J. Perry, and J. Montgomery Walking patterns of healthy subjects wearing rocker shoes. *Physical Therapy*. **65**(1985) 10:1483-9.

[9] R. Schmidt, C. Disselhorst-Klug, J. Silny, and G. Rau. A makerbased measurement procedure for unconstrained wrist and elbow motions. *Journal of Biomechanics* **32**(1999): 615–621.

[10] G. Wu, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *Journal of Biomechanics,* **35** (2002) 4: 543–548.

[11] G. Wu, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion -- Part II; shoulder, elbow, wrist and hand. *Journal of Biomechanics*. **38**(2005)5: 981-992.

[12] T. W. Lu, J. J. O'Connor. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *Journal of Biomechanics*. **32**(1999): 129–34.

[13] I. Kingma, M.P. deLooze, J.H. van Dieën, H.M. Toussaint, M.A. Adams and C.T. Baten, When is a lifting movement too asymmetric to identify low-back loading by 2-D analysis?, *Ergonomics* **41** (1998) (10): 1453–1461.