

A Kinematic Estimation of Functional Joint Rotation Centers of Whole Body

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Abstract— This study is about an estimation method of joint rotation centers. In order to apply motion capture (MoCap) data of the whole body of an actual person to digital manikins or computer graphics models, it is necessary to estimate each rotation center of joint and to define each posture of body segment from the MoCap data. We developed a kinematic estimation method of the functional joint rotation centers and the postures of the whole body. Using the estimation method, a unique model of the subject is made from MoCap data, which are applicable to clinical analysis.

Keywords—functional joint rotation center; kinematic estimation; digital manikin; whole body;

I. INTRODUCTION

With the recent advance of 3D motion detective system, researches of movement analysis of whole body have increased. These researches are not only in a clinical field like gait analysis using a clinical marker set like Helen-Hayes marker set [1] but also in an industrial field like ingress and egress motions of a car. Especially, it is important for the design of cars to apply the measured motion to a digital manikin like JACK (UGS Corp., [2]) or RAMSIS (HUMAN SOLUTIONS, [3]). Furthermore, also in the field of computer graphics, the measured motion is applied to CG character for creating the animation [4]. Nevertheless if the size of the model is the same as that of the measured subject, the gaps between the tips of the hand or the foot of actual persons and those of the models occur. The reason of this problem is due to the inconsistency of the structure between the model and actual human. However, it is difficult to model the anatomical structure rigorously.

Therefore, we developed a measuring method of the motion according to the structure of the model which consists of rigid segments and spheroid joints. When a subject revolves his or her body segments around joint in a certain motion, the joint rotation centers and the length of the segments can be estimated kinematically from the markers attached on the segments without anatomical knowledge. From these results, the subject's own model is defined. It is, to some extent, a dynamic calibration of the whole body. We named these rotation centers “functional joint rotation centers”. Moreover, the 3D posture of the subject can be also decided on by fitting this model to the measured data of markers.

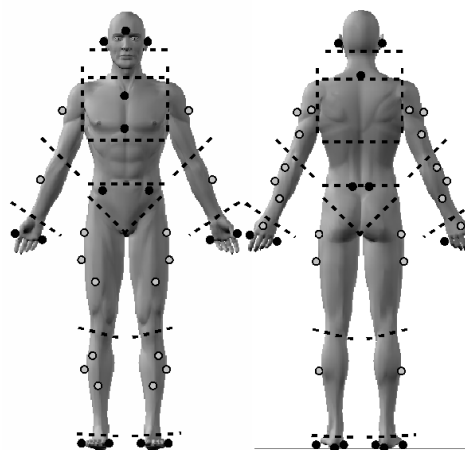
II. THEORY

A. Divide of Whole Body

Fig. 1 shows the divide of the whole body. Upper extremity consists of hand, forearm, and upper arm. Lower extremity consists of foot, shank, and thigh. Torso is divided into head, neck, chest, abdomen, and pelvis. As a whole, this model has 17 rigid segments. The joint between the adjacent segments are assumed to be a spheroid joint except shoulder joint. Shoulder joint has 6 degree of freedom, i.e. 3 translations and 3 rotations. This is because shoulder has the complex joint including clavicle, scapula, and humerus.

B. Condition of Measurement

When an optical 3D motion detective system is used for the measurement of movement of a subject, it is necessary to attach 3 markers on each segment at the least. A coordinate system in each segment can be decided from these markers. This coordinate system is named “marker coordinate system”. Under the condition of Fig. 1, the distance from a position in the segment to the proximal and distal end of the segment is constant, respectively. Using these assumptions, we proposed the estimation of the joint rotation center.



- Anatomical landmark (fixed position)
- Kinematic landmark (anywhere in segment)

Figure 1. Whole body model and marker position

The marker set is attached on anywhere in upper arm, forearm, thigh, and shank if the markers are not set in a straight line. However, in case of the other segments, the markers have to be attached on decided anatomical landmarks. This is because the definition of the coordinate system of the segment consists with anatomical knowledge.

C. Estimation Method of Functional Joint Rotation Center between 2 Segments

Fig. 2 shows arrangement of joint rotation center between upper and lower marker coordinate systems, e.g. knee. At time t , the joint rotation center, ${}^A\mathbf{P}_t^J$ is decided using the upper marker coordinate system, ${}^A\mathbf{R}_t^{SU}$ and the lower marker system coordinate system, ${}^A\mathbf{R}_t^{SL}$, respectively as

$${}^A\mathbf{P}_t^J = {}^A\mathbf{P}_{O_t}^{SU} + {}^A\mathbf{R}_t^{SU} {}^{SU}\mathbf{P}_t^J \quad (1)$$

$${}^A\mathbf{P}_t^J = {}^A\mathbf{P}_{O_t}^{SL} + {}^A\mathbf{R}_t^{SL} {}^{SL}\mathbf{P}_t^J \quad (2)$$

${}^A\mathbf{P}_{O_t}^{SU}$ and ${}^A\mathbf{P}_{O_t}^{SL}$ are the origin of the upper and lower marker coordinate systems in absolute coordinate system respectively. ${}^{SU}\mathbf{P}_t^J$ and ${}^{SL}\mathbf{P}_t^J$ are the joint rotation center in the upper and lower marker coordinate systems, respectively. When the segment revolves around the objective joint as the range of motion is filled, ${}^A\mathbf{P}_t^J$ of (1) and (2) is the same in the motion. In order to estimate ${}^A\mathbf{P}_t^J$, ${}^{SU}\mathbf{P}_t^J$ and ${}^{SL}\mathbf{P}_t^J$ in the motion named “positioning motion” are solved as minimizing the gaps of (1) and (2) by a conventional amoeba method [5]. These are the constant vectors in each marker coordinate system. Therefore, the length from the proximal end to the distal end of each segment is also constant. Using the results and the same marker set, the joint rotation center can be estimated in the other motions. This kinematic method is similar to that of Cappozzo [6], who validated that the rotation center of hip was estimated in head of femur.

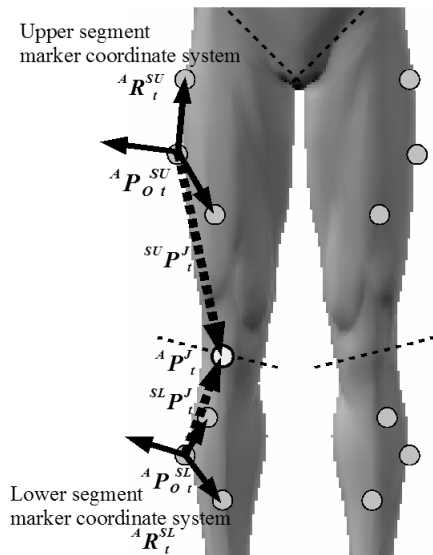


Figure 2. Arrangement of marker coordinate systems and rotation center of joint between 2 segments

D. Estimation Method of Joint Rotation Center of Shoulder

The method as mentioned earlier can not be used for the estimation of the joint rotation center of shoulder because upper arm and torso connects at plural and complex joints. Some methods were proposed about the rotation center of shoulder joint [7][8][9][10][11]. However these methods are not consistent with the whole rigid model we suppose. Referring to a kinematic modeling method of shoulder [12], we developed another estimation method about joint rotation center of shoulder [13]. Fig. 3 shows arrangement of joint rotation center of shoulder and markers at time t and $t + dt$. If dt is very short, ${}^A\mathbf{P}_t^J$ and ${}^A\mathbf{P}_{t+dt}^J$ are fixed on a nearly similar point in the absolute coordinate system. Therefore the relationship between the distances from each position of n th marker, ${}^A\mathbf{P}_{nt}^M$ or ${}^A\mathbf{P}_{n t+dt}^M$ to ${}^A\mathbf{P}_t^J$ or ${}^A\mathbf{P}_{t+dt}^J$ is shown as

$$|{}^A\mathbf{P}_t^J - {}^A\mathbf{P}_{nt}^M| = |{}^A\mathbf{P}_{t+dt}^J - {}^A\mathbf{P}_{n t+dt}^M|. \quad (3)$$

Equation (3) is expanded into linear equation as

$${}^A\mathbf{P}_t^J = \mathbf{A}_t^{-1} \mathbf{B}_t. \quad (4)$$

\mathbf{A}_t and \mathbf{B}_t are the matrixes which consist of the expanded components of ${}^A\mathbf{P}_{nt}^M$ and ${}^A\mathbf{P}_{n t+dt}^M$. If the upper arm does the pre-established positioning motion, ${}^A\mathbf{P}_t^J$ of (2) and (4) is the same in the motion. In order to estimate ${}^A\mathbf{P}_t^J$, ${}^{SL}\mathbf{P}_t^J$ are solved as minimizing the gaps of (2) and (4) in the same way of the estimation of the other joint rotation centers.

This accuracy of the method is affected how to move the upper arm. The detail is referred in [13]. When the method was applied to a known shoulder dummy model, the average errors in the appropriate positioning motion were 4.1mm in the lateral direction, 2.5mm in the sagittal direction, and 3.2mm in the vertical direction.

E. Definition of Segment Coordinate System

The whole body model is made by connecting the estimated joint rotation centers. We defined each segment coordinate system which is applicable to clinical analysis. X, Y, and Z-axis in the segment coordinate system are defined as flexion-extension axis, abduction-adduction axis, and supination-pronation axis, respectively.

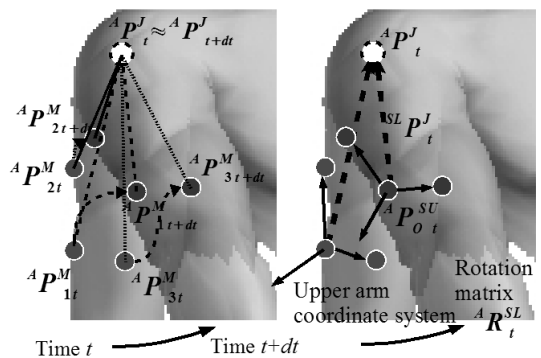


Figure 3. Conditions of upper arm and shoulder at time t and time $t + dt$ and arrangement of marker coordinate system of upper arm

Z-axis is along the long axis of the segment which is made by connecting the distal rotation center and the proximal rotation center. The flexion-extension axis of the elbow and the knee is calculated by a vector product of the long axis of the upper segment and that of the lower segment, when the segments connecting to the elbow and the knee are not straight in positioning motion. The axis is described in each marker coordinate system, and it is calculated by fitting to the measured marker set in the other motions. About hand, foot, and torso segment, each frontal plane is defined from the anatomical landmarks shown by Fig. 1 and the estimated long axis. The lateral bending axis is calculated by a vector product of the plane and the long axis.

III. MEASURING RESULTS

A. Measurement and Estimated Joint Rotation Center

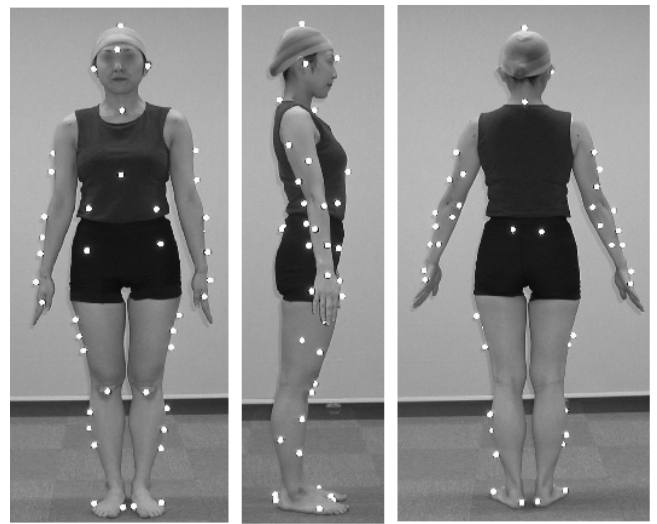
We measured 57 markers attached on the whole bodies of 2 subjects (subject 1: male, 1.70m, 24yrs; subject 2: female, 1.58m, 33yrs) with a motion capture system, ViconMX (Vicon Peak Inc.). Fig. 4 is the example of the estimated result of subject 2. Fig. 4(a) is the marker set on subject 2. Fig. 4(b) is the measured marker set in a pose e.g. yoga and Fig. 4(c) shows the estimated joint rotation centers and segments. As a result, some estimated joints are separated. This is because 2 joint rotation centers every joint are calculated from the marker set of the upper segments and the lower segments in motion. If the arrangement of these markers on the segments is exactly correspond with that in the positioning motion, 2 joint rotation centers locate in the same position. However, these marker sets are deformed by skin movement artifact. Moreover, the structures of human body, especially the degrees of freedom of the joint are not the same as the model we proposed rigorously. These problems suggest the necessity to minimize the gaps between the positions of markers in motion and those in positioning motion using a method such as inverse kinematics.

B. Locations of Joint Rotation Centers in Body Shape

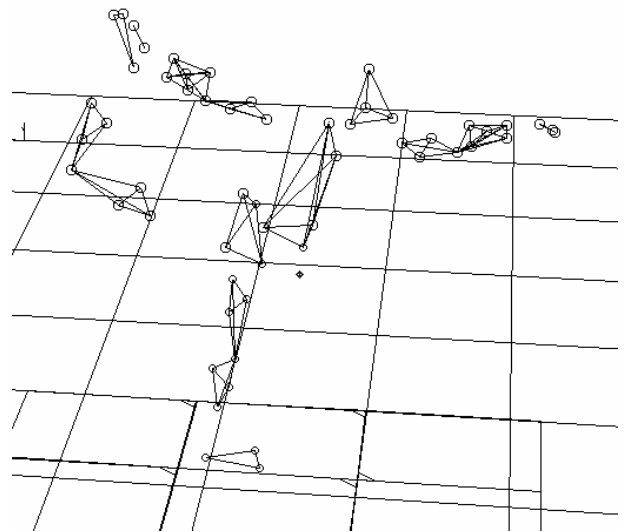
In order to examine where the functional joint rotation centers are arranged in the body, we also measure the body shape of the same subjects with a 3D body shape scanner, Body Line Manager (Hamamatu Photonics K.K.). As shown by Fig. 5, the estimated joint rotation centers can be superimposed on the shape data as the mutual marker sets match each other.

Regarding elbow, the estimated joint rotation centers was located in the slightly lateral side in the shape, where is around the head of radius. In fact, forearm twists through the radius turns on the ulna as a rotation axis [14]. Knee was the same as elbow, but these 2 joints revolve almost like a hinge joint. Therefore, each rotation center was just estimated on a point of each flexion-extension axis, to be precise.

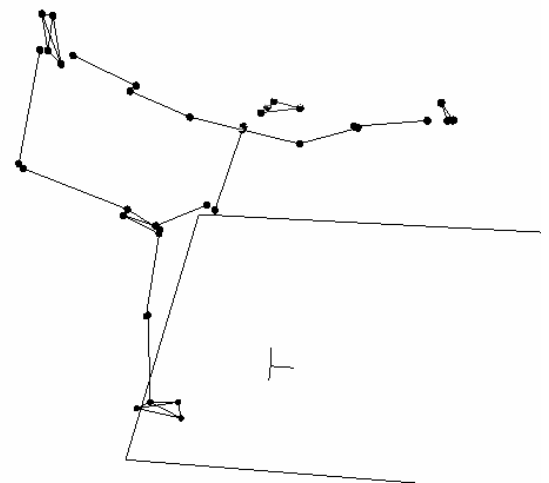
The position of the rotation center of ankle was located slightly under the malleolus. The planter flexion- dorsiflection axis runs through the medial malleolus and the lateral malleolus, but the inversion-eversion axis runs through the lower part of the trochlea of talus [15]. These 2 axes do not intersect. Therefore, the joint rotation center of ankle was estimated as a compound point of these 2 two axes.



(a) Attached marker set on subject 2



(b) Measured markers in a pose e.g. yoga



(c) Estimated joint rotation centers

Figure 4. Estimation of joint rotation centers

About the joint rotation centers of torso, the estimated centers were located ventrally in the sagittal plane, but the segments seem to run parallel with the spinal curvature. This result is considered that the positions of the estimated centers are related to the radius of the curvature when the torso is bending. Moreover, the joint between the abdomen and the pelvis was not located at the center of the torso, because the distortion of the position of markers on the abdomen and the pelvis were larger than that on the other segments. Besides the subjects could not do the completely bilateral symmetrical positioning motion of torso. This result suggests that the method has to be improved adding to the assumption of bilateral symmetry in case of measuring normal subjects.

C. Validation of the definitions of 3D angles

We measured normal gait. Fig. 6 shows the angular patterns of the joint of the lower extremity. In Fig. 7, the hip always seems to flexure relatively to the pelvis. This is because the posture of the pelvis is just inclined forward according to this estimation method. Except this difference for the definition, these patterns are almost the same as the generally known patterns. Therefore, the definition is considered to be available for clinical and anatomical analyses about lower extremity. Hereafter, we will need to validate also the angles of upper extremity and torso.

IV. CONCLUSION

We developed a kinematic estimation method of the functional joint rotation centers and the postures of the whole body. Using this method, a unique model of a subject is made from MoCap data, and the calculated 3D angles are useful for clinical and anatomical analyses. However, since the method depends on positioning motions, we will improve the method and decide more suitable positioning motions, too.

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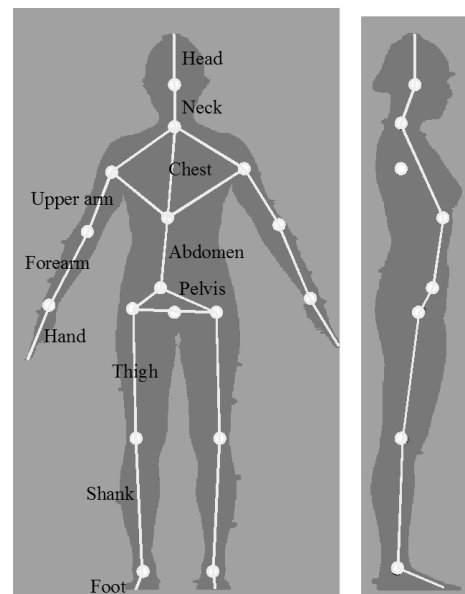


Figure 5. Arrangement of the estimated rotation centers in the body

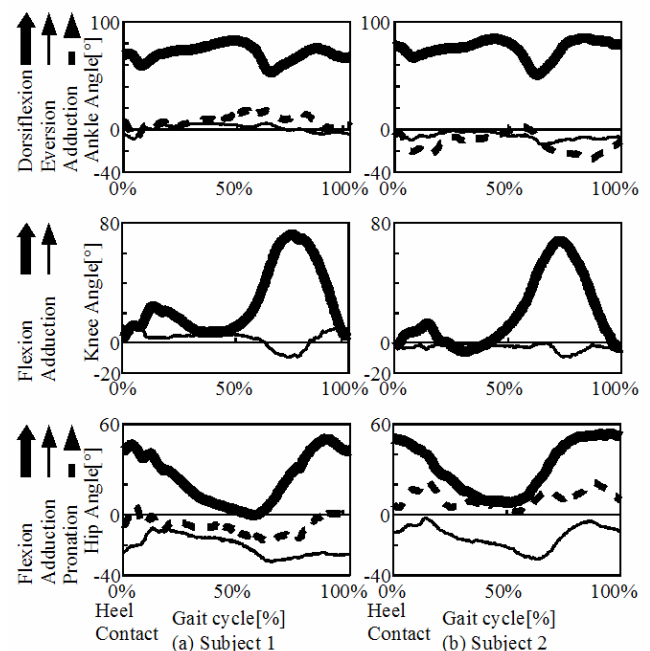


Figure 6. 3D angles of lower extremities in gait

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