Feasibility Study of Inertial Sensor-based Joint Moment Estimation Method During Human Movements

A Test of Multi-link Modeling of the Trunk Segment

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Abstract: The conventional method of estimating joint moments needs kinematic data measured with a 3D optical motion measurement system and ground reaction forces measured with force plate. However, the conventional method is limited generally to laboratory use because of the required measurement systems. Therefore, we proposed a convenient method to estimate joint moments from measurements only with inertial sensors for application to clinical evaluation of motor function of paralyzed and elderly subjects. In this paper, multi-link modeling of the trunk was examined for reliable estimation of joint moments only from measured data with inertial sensors attached on the body. Body segment parameters (segment length and mass, center of mass location and moments of inertia) were calculated from anthropometric data. Experimental test with 3 healthy subjects showed that segmented trunk model estimated joint moments better than a rigid trunk model for squat and sit-to-stand movements. The estimation results were not different largely between the 5-link model that modeled the trunk by 3 segments and the 4-link model that modeled the trunk by 2 segments. However, trunk modeling for 4-link model was suggested to be appropriate when the upper and the middle trunk segments of the 5-link model were modeled as one segment.

1 INTRODUCTION

Difficulty in standing up is one of important factors of preventing independent daily life for elderly or motor disabled subjects. Joint moments during sit-to-stand movement can evaluate decrease of muscle force of lower limbs, from which a cause of the difficulty in standing up can be estimated. However, joint moments can not be measured directly with sensors or measurement equipments, especially during human movements. Therefore, generally, joint moments are estimated by indirect means from data measured with a camera based 3D motion analysis system and a force plate system. However, using these systems limits measurement environment, especially to laboratory, and takes many costs.

In our previous study, a method of estimating joint moment only using inertial sensors was proposed and shown to be feasible in our preliminary test (Mori and Watanabe, 2011; Watanabe et al., 2012). Although the proposed method can remove the limitation of measurement environment and reduce the cost, estimated joint moments showed large difference in comparison with the conventional method using 3D motion analysis system and force plate. In addition, our preliminary test suggested that 3-link model of the body, which modeled the trunk as one segment, can decrease the difference between inertial sensor based moment estimation method and the conventional method in comparison with 4-link model, which modeled the trunk by 2 segments (Mori and Watanabe, 2011). However, Zijlstra and Bisseling reported that segmented trunk model estimated hip abduction moment using acceleration and angular velocity signals better than rigid trunk model (Zijlstra and Bisseling, 2004).

Therefore, this paper aimed at reexamining the feasibility of joint moment estimation only using inertial sensors. Especially, in this paper, multi-link models of the trunk were tested in estimation of joint moments only from measured data with inertial sensors attached on the body. Body segment

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parameters (segment length and mass, center of mass location and moment of inertia) were calculated from anthropometric data reported by Ae et al., (1992) and Kouchi and Mochimaru (2005). Since there were several definitions of trunk segmentation, based on the model used by Young et al., (1983), 5-link model consisted of 3-trunk segments, 2 types of 4-link model including 2 trunk segments and 3-link model that uses rigid trunk model were examined in joint moment estimation comparing to reference data of joint moment estimated by the conventional method.

2 ESTIMATION METHOD OF JOINT MOMENTS

2.1 Rigid Body Link Model

Figure 1(a) shows the rigid body link model for human body (5-link model), which consists of the shank (i=1), the thigh (i=2), the lower trunk (i=3), the middle trunk (i=4) and the upper trunk (i=5). The foot was fixed on the ground. Definition of inclination angle of each segment for the 5-link model is also shown in Figure 1(a). Each segment was assumed to move in the sagittal plane. The boundaries between the middle and the lower trunk segments and between the upper and the middle and trunk segments were defined at the highest point of the iliac crest and the lower end of the rib, respectively. Here, head and upper limbs were included into the upper trunk segment.

The anthropometric data reported by Ae et al., (1992) used the model that segmented the trunk by the lower end of the rib. For this modeling, the 4-link model that segmented the trunk by the lower end of the rib was defined (4-link-A-model). As another 4-link model, trunk modeling segmented by the highest point of the iliac crest was also defined (4-link-B-model). Here, the lower trunk by Ae et al., (1992) means the middle-lower trunk of the 5-link model. Therefore, body segment parameters of the lower trunk of the 5-link and the 4-link-B models were calculated from those of the lower trunk reported by Ae et al., (1992), in which the middle trunk was approximated by an elliptic cylinder with the density reported by Clauser et al., (1969). Then, body segment parameters for the upper-middle trunk segment were calculated by synthesizing those of the upper and the middle trunk segments. Size parameters in calculation of the synthesizing were obtained from average values in the AIST Human body size database (Kouchi and Mochimaru, 2005).

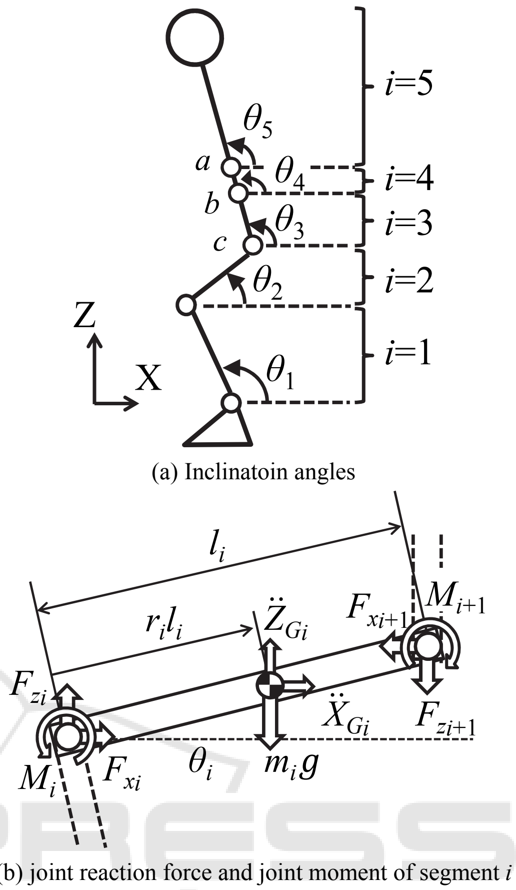

Figure 1: Definitions of segment inclination angle, joint reaction force and joint moment. a, b and c shows the lower end of the rib, the highest point of the iliac crest and the great trochanter, respectively.

2.2 Estimation of Joint Moment

Center of mass location of each segment was calculated at first. Each segment length was calculated from measured height of each subject by using statistically obtained segment length ratio (Kouchi and Mochimaru, 2005). The center of segment mass locations of body segments were calculated from measured inclination angles of segments and the calculated segment lengths. Acceleration of the center of mass and angular acceleration of inclination angle of each segment that were required in estimation of joint moments were calculated by the differential using third order low pass differentiation algorithm (Usui and Ikegaya, 1978).

Based on Figure 1(b), equations of translational motion and rotational motion of the center of mass of each rigid body segment are shown by the followings:

$$m_i\ddot{X}_{Gi} = F_{x_i} - F_{x_{i+1}} \tag{1}$$

$$m_i\ddot{Z}_{Gi} = F_{z_i} - F_{z_{i+1}} - m_i g \tag{2}$$

$$\begin{aligned} I_i\ddot{\theta}_i = M_i - M_{i+1} &+ (r_iF_{x_i} + (1-r_i)F_{x_{i+1}})l_i\sin\theta_i \\ &- (r_iF_{z_i} + (1-r_i)F_{z_{i+1}})l_i\cos\theta_i \end{aligned} \tag{3}$$

Here,
i : segment number
m_i : segment mass
l_i : segment length
r_i : center of mass ratio from the lower end
I_i : moment of inertia
M_i : joint moment
F_{x_i}, F_{z_i} : joint reaction forces
$\ddot{X}_{Gi}$, $\ddot{Z}_{Gi}$: acceleration of segment center of mass position
θ_i, $\ddot{\theta}_i$: inclination angle and its angular acceleration
g : gravitational acceleration

Joint reaction forces are calculated from Equations (1) and (2), and then values of the forces are substituted in Equation (3). Each joint moment can be estimated by solving these simultaneous equations with the assumption that no external force acts to the upper segment.

3 EXPERIMENTAL METHODS

Figure 2 shows experimental set up. In order to examine the joint moment estimation method, human movements were measured with optical 3D motion measurement system (OPTOTRAK, Northern Digital), force plate (9286A, Kistler) and wireless inertial sensors (bluetooth, InvenSense MPU-9150, ERi). Three healthy subjects (male, 21-23 y.o.) performed 5 times of 4 movements: 2 types of squat movement (movement time was 6s and 9s) and 2 types of sit-to-stand movement (normal and forward inclination of the trunk imitating elderly persons).

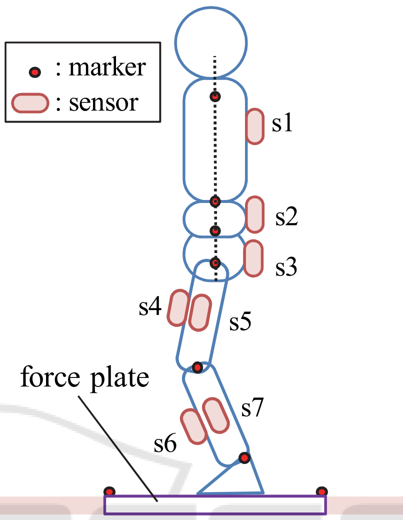

Figure 2: Experimental setup of measurement of movement with inertial sensors, 3D motion measurement system and force plate.

Inertial sensors were attached on the skin with double-sided adhesive tape near the center of mass location to the front and the lateral sides of the shank and the thigh of left lower limb, and the back side at upper, middle and lower trunk segments as shown in

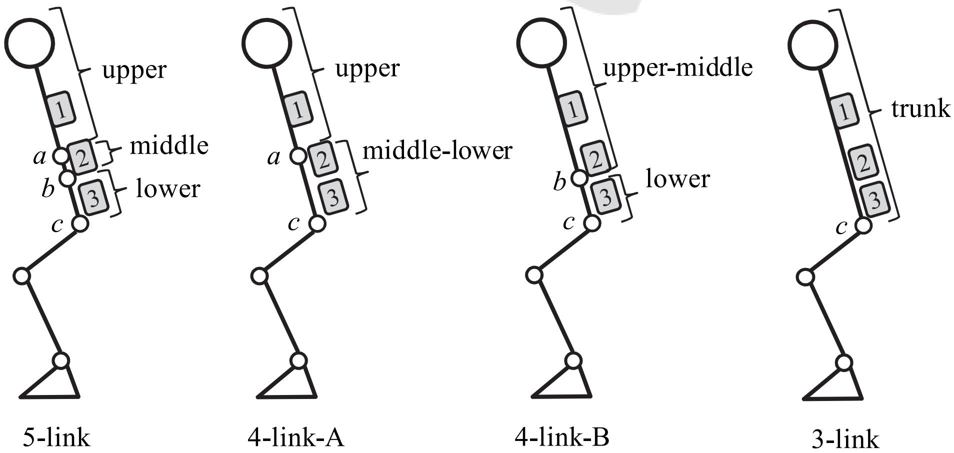

Figure 3: Multi-link models tested in this paper and sensor attachment positions to the trunk segments. 1, 2 and 3 shows inertial sensors, and *a*, *b* and *c* shows the lower end of the rib, the highest point of the iliac crest and the great trochanter, respectively.

Figure 2. Markers for the 3D motion measurement system were attached on the left side of subject, in which positions were the acromion, along the long axis of the trunk at the same height as the lower end of the rib and the highest point of the iliac crest, the great trochanter, the lateral femoral condyle, and the lateral malleolus.

Figure 3 shows sensor attachment to trunk segments of each link model. Reference moment data were calculated by the conventional method from measured data with 3D motion measurement system and force plate for each link model.

Inclination angles were obtained by calculating the integral of measured angular velocity with inertial sensor, in which integrated errors caused by offset of gyroscope was removed assuming constant offset value during movement. The measured inclination angles with inertial sensors and estimated joint moments were evaluated for movement period that were detected by angular velocity of the shank for squat movement and by ground reaction force for sit-to-stand movement, respectively.

4 RESULTS

4.1 Inclination Angles

Segment inclination angles measured with inertial sensors were compared to those angles measured with 3D motion measurement system. Calculation error of the angle by the integral of angular velocity was corrected by linear approximation of the integral error. Figure 4 shows average RMS (root mean square) errors of angles between inertial sensor and 3D motion measurement system. For inclination angles of the shank and the thigh segments, sensors attached to the lateral side showed lower values of RMS error than those of sensors attached to the front side. For the angles of trunk segment of the 3-link model, the sensors 1 and 2 that were attached to the upper and the middle trunks showed small RMS errors, although the sensors 2 showed the lowest errors. For angles of the middle-lower trunk segment of the 4-link-A model, sensor 3 attached to the lower trunk showed smaller RMS errors. Sensor 1 attached to the upper trunk showed smaller RMS errors for angles of the upper-middle trunk segment of the 4-link-B model.

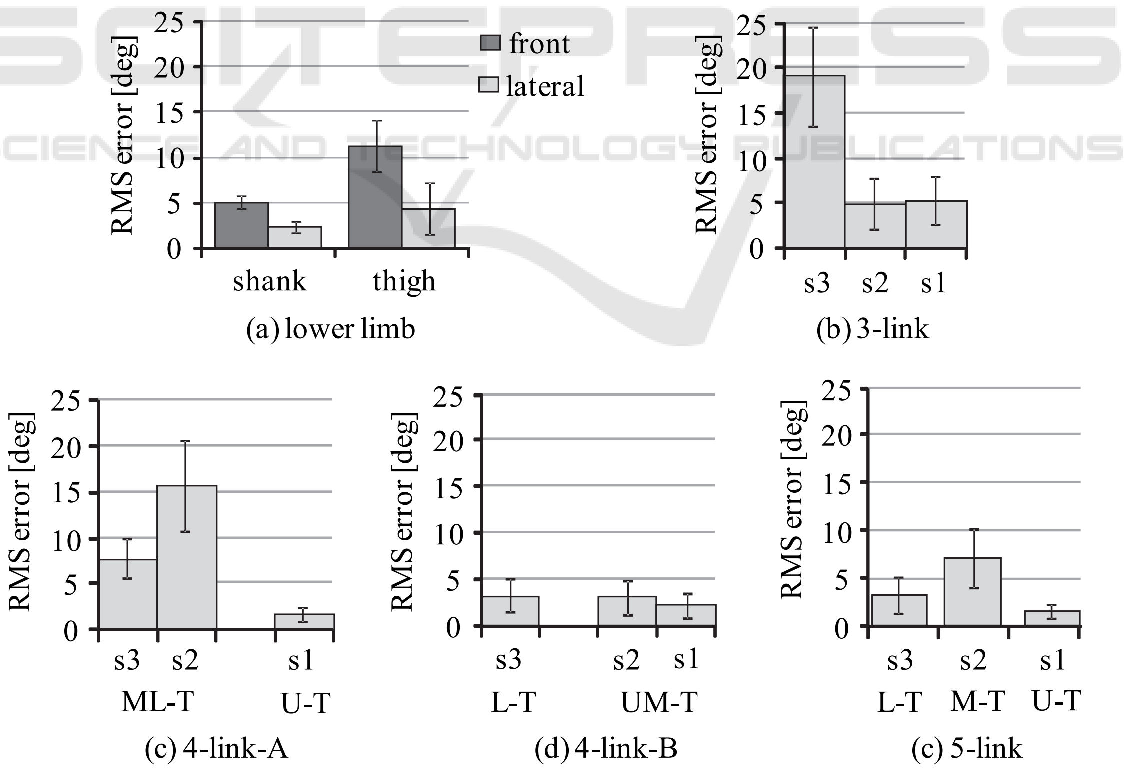

Figure 4: RMS values of segment inclination angles measured with inertial sensors and the 3D motion measurement system. s1, s2 and s3 show sensors attached to the trunk shown in Figures 3 and 4. RMS values were calculated for shank and thigh segments, and a rigid trunk segment of 3-link model, and upper (U-T), middle (M-T), lower (L-T), upper-middle (UM-T) and middle-lower (ML-T) trunk segments of 4-link and 5-link models.

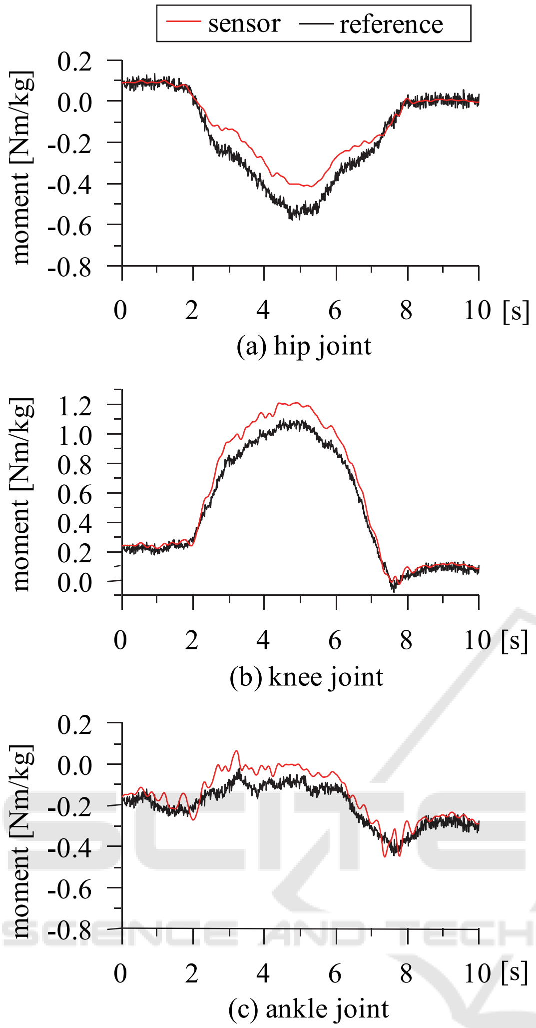

Figure 5: Examples of estimated and reference joint moments during squat movement (5-link model).

From above results, sensors that showed the lowest RMS errors were used for measurement inclination angles of segments in joint moment estimation.

4.2 Joint Moment

Joint moments were estimated by using inclination angles measured with inertial sensors determined in the previous section. Figure 5 shows examples of estimated and reference joint moments during squat movement with the 5-link model. Estimated moments were normalized to the weight of subject. The inertial sensor based joint moment estimation method was suggested to estimate joints moments appropriately.

RMS values of differences between reference

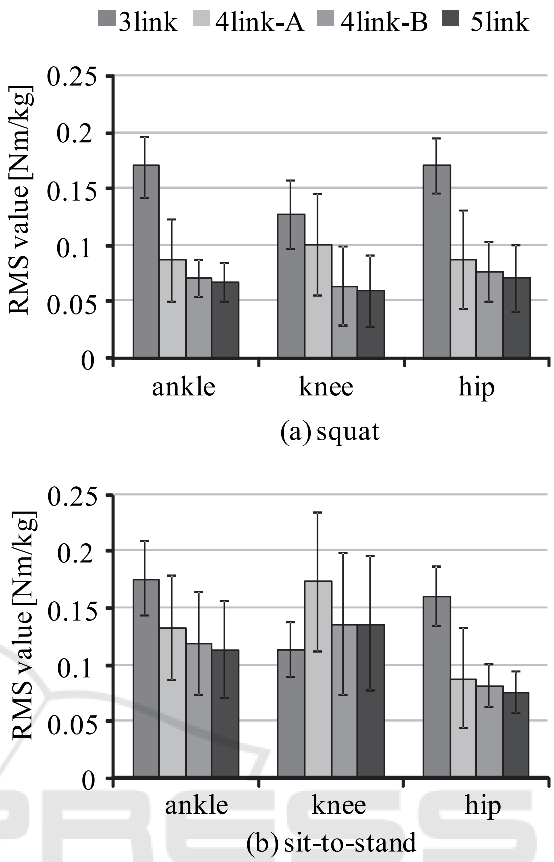

Figure 6: RMS values of estimated joint moments only with inertial sensors.

moment data and the estimated moments were shown in Figure 6. For squat movement, the RMS values of the 5-link model were the smallest and the 4-link-B model showed similar RMS values as those of the 5-link model, which were less than 0.1 Nm/kg in average. Although the 4-link-A model showed smaller RMS values than those of the 3-link model, the average value and variations were larger than those of the 5-link and 4-link-B models. RMS values of the estimated moments shown in Figure 6 were 0.098, 0.112 and 0.074 for the hip, knee and ankle joints, respectively. For sit-to-stand movement, estimation of ankle and hip joint moments showed similar results as the squat movement. However, knee joint moment was estimated well by the 3-link model.

In order to validate the estimation method, inclination angles measured with 3D motion measurement system were substituted for the angles in Equations (1)-(3) and joint moments were estimated by the estimation method described in Section 2.2 without ground reaction forces. The

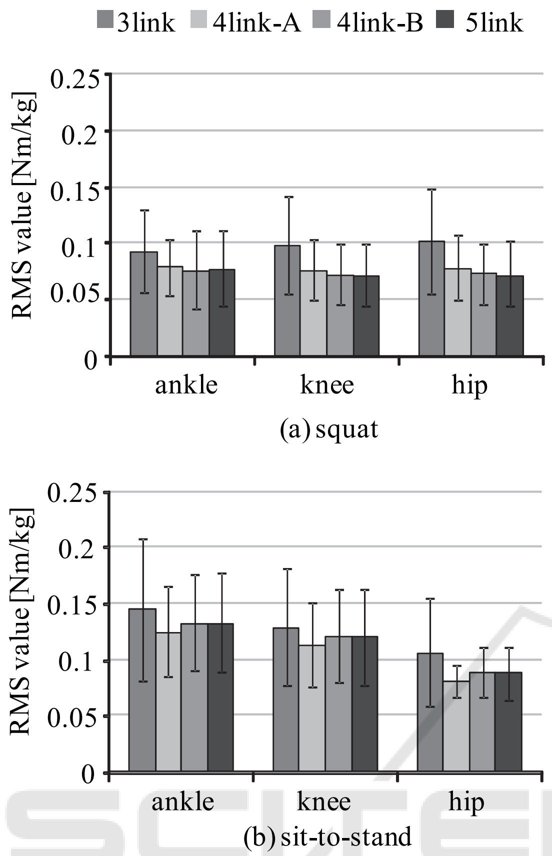

Figure 7: RMS values of estimated joint moments using inclination angles measured with the 3D motion measurement system and no ground reaction forces.

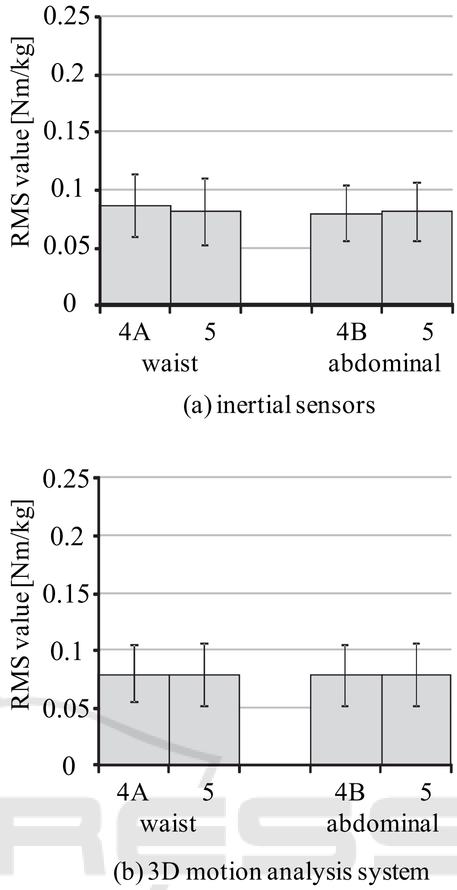

Figure 8: RMS values of trunk joints moments estimated without ground reaction force. 4A, 4B, 5 represents link model. Waist and abdominal mean joints between the middle and the lower trunk segments (at the highest point of the iliac crest) and between the upper and the middle trunk segments (at the lower end of the rib), respectively.

results were also compared to the reference moment data as shown in Figure 7. Although 3-link model showed the largest RMS values for both movements, most of the values were smaller than those of estimation with inertial sensor signals. For the squat movement, similar results were obtained as the results with inertial sensors. Although the 4-link-A model showed smallest RMS values for sit-to-stand movement, the differences from those of the 5-link and 4-link-B model were not so large.

The results of Figures 6 and 7 suggest that the 4-link and the 5-link models could estimate joint moment better than 3-link model. However, RMS values of the knee joint moment and some variations of RMS values were larger and than those of the 3-link model for the sit-to-stand movement with inertial sensors.

The 4-link and the 5-link models can estimate joint moments at the joint between trunk segments. Estimated joint moments of trunk segments were compared to the results calculated by the conventional method. RMS values were shown in Figure 8. RMS Values of joint moments of trunk segments were similar to those of the hip joint moment estimation, which were less than 0.1 Nm/kg. These results were almost same between the 4-link and 5-link models. Segment inclination angles measured with 3D motion measurement system also showed similar results with the inertial sensor based method.

5 DISCUSSIONS

For measurement of inclination angle of lower limb with inertial sensors, sensors attached to the lateral side showed smaller RMS errors than those of sensors attached on the front side as shown in Figure 4(a). In our previous study, inclination angles of lower limb segments measured with inertial sensors attached to the front side during walking showed RMS errors less than about 4deg in average in comparison with the 3D motion measurement system. The measurements performed in this paper were during squat and sit-to-stand movements that involve large hip and knee flexion movements, which were different from waking. Those large flexion movements were considered to cause differences in measurement results between sensors and markers. That is, deformation of muscles and sitting on the stool before standing up are considered to move markers and sensors differently.

As for the trunk inclination angles, 4-link-B model showed the smallest RMS errors as shown in Figure 4. Sensor 1 could measure inclination angles of the upper trunk and the upper-middle trunk with small RMS values. This suggests that movements of the upper and the middle trunks are similar even in the squat and the sit-to-stand movements. Therefore, 4-link-B model that uses the upper-middle trunk segment is considered to be appropriate. Although RMS values of the middle trunk of 5-link model was large, there was a possibility that angle measurement with the 3D motion measurement system (markers on the highest point of the iliac crest and the lower end of the rib) were affected by movements of skin or subcutaneous fat tissue during trunk bending movement.

The 5-link and the 4-link-B models showed similar good RMS values of joint moment estimation. The 4-link-A model showed increase of variation of RMS values of hip joint moment for both movements and ankle joint moment for squat movement, and the largest RMS values of the knee joint moment for the sit-to-stand movement in estimation with inertial sensors. On the other hand, validation test of the joint moment estimation method shown in Figure 7 suggested that the 5-link and 4-link models can estimate joint moments with similar RMS value. The deterioration of the 4-link-A model in moment estimation with inertial sensors is considered to be caused by large difference in inclination angle of the middle-lower trunk segment.

Variations of RMS values increased for sit-to-stand movement as seen in Figures 6 and 7. The variation was considered to be caused by differences among subjects. Error in modeling subject by rigid body link model is considered to be caused by using anthropometric data that were statistic average values. That is, physical constitution of each subject was different from average.

RMS values in joint moment estimation with inertial sensors were less than 0.1 and o.15 for squat and sit-to-stand movements, respectively. As shown in Figures 6 and 7, the 5-link and the 4-link-B models with inertial sensors showed similar RMS values in joint moment estimation with the 3D motion measurement system and no ground reaction forces. These suggest that the method of joint moment estimation using inertial sensors in this paper is feasible. However, further studies are required to make clear if the RMS values are acceptable or not, increasing the number of subjects.

Joint moment estimation of trunk segments showed similar RMS values as those of the hip joint moment. It is considered that this is because moments of trunk segments were similar values as those of the hip joint, since the segment masses and lengths of the middle and the lower trunk segments were smaller and shorter than those of the upper trunk segment.

6 CONCLUSIONS

This paper aimed at determination of feasibility of the method of estimating joint moment only using inertial sensors. Multi-link model of the trunk was tested in joint moment estimation after calculations of body segment parameters based on anthropometric data. The proposed method could estimate similar waveform of joint moments as those of the conventional method. Segmented trunk model estimated joint moment better than a rigid trunk model. The estimation results were not different between the 5-link model that modeled the trunk by 3 segments and the 4-link model that modeled the trunk by 2 segments. However, trunk modeling for 4-link model was found to be appropriate when the upper and the middle segments were modeled as one segment in case of using inertial sensors. The results of this paper suggested that the inertial sensor based joint moment estimation is feasible. Further tests are expected to improve reliability of the inertial sensor based joint angle estimation method.

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