Master's Thesis
석사 학위논문

Simple calculation of joint moment for lower extremity during sit to stand motion

Seoyoon Hwang (황 서 윤 黃 憰 允)

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Robotics Engineering. The study was conducted in accordance with Code of Research Ethics[1)]

01. 06. 2017

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Accepted in partial fulfillment of the requirements for the degree of Master of Science.

11. 24. 2016

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201523009

황 서 윤. Seoyoon Hwang. Simple calculation of joint moment for lower extremity during sit to stand motion. Department of Robotics Engineering. 2017. p.22 Advisors Prof. Kim, Jonghyun, Prof. Lee, Yang-Soo

Abstract

Muscular strength of elderly people decreased when they get older. Decreased muscular strength made decrease in quality of life of the elderly. Therefore, muscular evaluation was needed. Maximum joint moment during sit to stand could be evaluation method to maximum muscular strength to do activities of daily lives of elderly. Existed system to measure joint moments during sit to stand motion was not clinically friendly. Therefore, goal of the study was to make simplified system to measure joint moment during sit to stand motion.

To make simplified system, simplified equation which joint position and ground reaction force was used to decrease sensors to detect kinematic components. Joint position during sit to stand was estimated based on the sitting posture. Shank angle displacement during sit to stand was measured by IMU to add sitting shank angle. Thigh angle was estimated by relationship between thigh segment and edge of chair.

Joint moment for lower extremity was calculated by estimated segment angle. To see accuracy, joint moment from propsoed system was compared with joint moment from Mocap.. Most of maximum lower extremity joint moment error was less than the 20% in symmetric and asymmetric sit to stand. Also correlation coefficient was over 0.95.

For the future research, method to estimated segment angle needed to be modified to increase accuracy and validation to the elderly.

Keywords : Muscular strength, Sit to stand, Maximum joint moment

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Ⅰ. INTRODUCTION

1.1 Background

People experienced muscle strength decline when they get older. Muscle strength decline was occurred about 1.5% to 5% in a year when people's age over 50^{th} by skeletal muscle and bone mass decreasing [12]. Muscle strength weakness associated with low physical performance and disability [19]. Muscle strength needed to perform some ADL became similar to maximum capabilities of muscular strength at knee joint by muscle strength weakness [11]. Therefore, decreasing ability to do independent activities of daily living (ADL) [23] and fall [22] appeared at elderly. Two phenomenon made decreasing in the elderly's quality of life [22]. Also, muscle strength related to mortality of elderly [19]. To prevent the muscle strength decrease, muscular strengthening was needed for elderly [3] if needed. To give information of muscle strength decrease, muscle strength needed to evaluate by maximum voluntary joint moment [4].

Sit to stand was movement standing from sitting. Sit to stand was precursor of most of ADL movement, therefore it was often used at daily lives. Among motion of ADL, sit to stand was called as motion with great mechanical demands [24, 33]. Since, sit to stand generated higher strength than other ADL movement. Example, sit to stand had larger values of load to assigned to joints and hip joint flexion moment than locomotion. Moreover, knee joint moment was higher than walking.

Sit to stand was one of ADL which muscular strength needed to perform similar to maximum capabilities of muscular strength of elderly. Therefore, maximum moments of lower-limb joints (hip, knee and ankle) during sit to stand would be performance indices to show the elderly's lower-limb muscle strength for daily life.

1.2 Joint moment calculation during sit to stand

Joint moment of lower extremity (ankle, knee and hip) during sit to stand motion was calculated by inverse dynamics. Force for calculation was measured by force plate and joint position was measured by motion capture system (Mocap.). Force plate and Mocap. were measuring force and three dimensional kinematics and kinetics accurately. They used as standard system to compare. However, force plate and Mocap. costed a lot of money to be equipped. Moreover, force plate and Mocap. needed quite a lot of space and technique to handle the system

[10]. Therefore, force plate and Mocap. were impractical to be used in clinical environment.

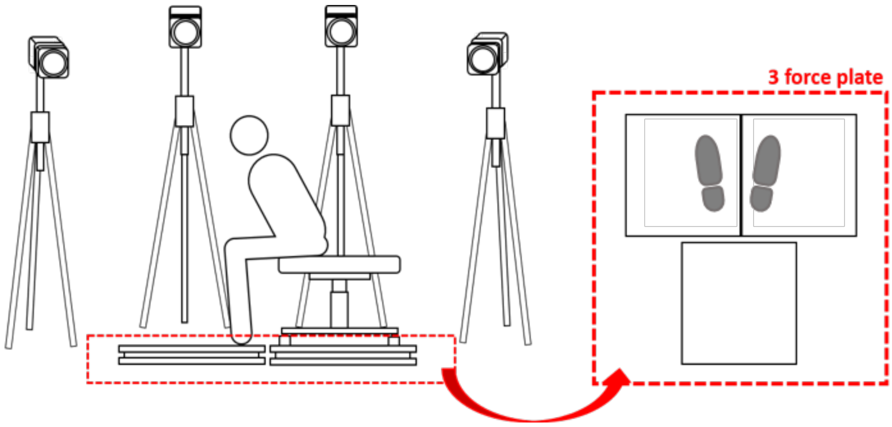


Figure 1. Conventional system to measure joint moment

To overcome the limitation of force plate and Mocap., studies to exchange the sensors was done. Adachi et. al. [1] developed system called ‘DOCTOR’S EYE’ by using Kinect to replace Mocap. by Kinect. DOCTOR’S EYE detected the movement of sit to stand by detecting z-directional movement and analyzed to get kinematic components (angle, (angular) velocity, and (angular) acceleration). Ground reaction force was estimated by angle information which gathered by Kinect. Accuracy of system was shown by just segment length error. Other result they estimated hadn’t analyze accuracy. Also, joint moments of lower extremity showed different tendency of movement reference document they provided. Validation to estimate joint moment needed to be improved.

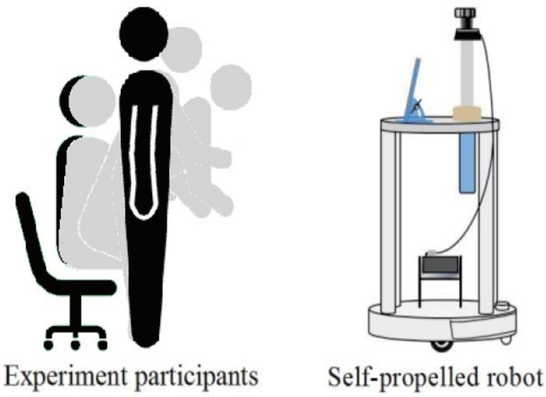


Figure 2. System of DOCTOR’S EYE

Kodama et. al. [13] developed system to measure joint moments during sit to stand motion using by inertia measurement unit (IMU). Total 4~5 IMU needed to make 4~5 link segmented model. IMU was located at body segment center of mass of each subject to measure segment angle and kinematic components of segment center. Ground reaction force was estimated and joint moment calculated by top-down method. Proposed system of Kodama shown RMS value of 0.12Nm/kg for knee joint moment and ankle joint moment and 0.08Nm/kg for hip joint moment.

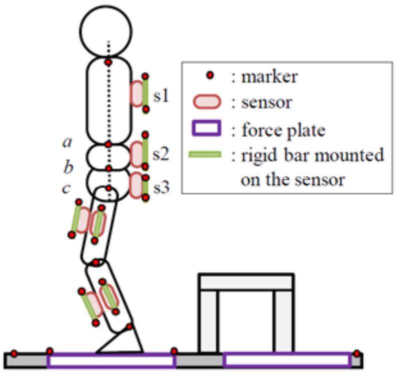


Figure 3. Proposed system of Kodama

This system mounted many sensors to the human body. Sensors mounted accurately to center of mass. This system assumed symmetrical movement which not considering asymmetrical movement. However, asymmetrical joint moment for lower extremity shown when elderly perform sit to stand motion [17]. Asymmetrical movement to do sit to stand motion had to be considered to estimate joint moment for elderly. Sensor mounting method and assumption for sit to stand movement needed to be improved.

1.3 Goal of study

The goal of study was proposing clinical friendly system to measure maximum joint moment during sit to stand. To make clinically friendly system, few sensors mounted to the body of patient and roughly. Moreover, system should consider asymmetric movement. Conventional system needed to be simplified.

Proposed system was consisted by simplified joint moment calculation and segment angle estimation. Simplified joint moment calculation method [32] was used, which didn't use acceleration and velocity to calculate joint moment by estimating quasi-static motion. Link-segmented model with 2 degree of freedom which consisted by shank and thigh segment was used to estimate segment angle. Segment angle during sit to stand was estimated by adding shank angle displacement which measured by IMU to shank angle during sitting posture estimated by inverse kinematics. Thigh angle was calculated by relationship between thigh segment at seat off and edge of chair which FSR was placed.

For the assessment, ten subjects were participated for the validation of experiment and three subjects were participated to see possibility of applying system to the asymmetrical movement. To see accuracy, proposed system result was compared with Mocap. result (golden standard). For evaluation, error between proposed system and golden standard had been seen by RMSE, root mean square percentage error (RMSPE). Correlation coefficient was calculated to similarity in proposed system and golden standard.

Ⅱ. NOMENCLATURE

Table 1. List of nomenclature

a_{com}	Acceleration of center of mass of body segment
c	Tangent of thigh angle
d	Length between thigh segment and position of FSR
g	Gravitational acceleration
j	Joint – 1 = ankle, 2 = knee, 3 = hip
k	Body segment – 1 = foot, 2 = shank, 3 = thigh
l	Segment length
m	Body segment mass
$r_{j\to c_k}$	Position difference of joint position to center of mass position
t	Time
F	Joint reaction force
F^i	Inertia joint force
F^s	Static joint force
H	Height
I_o	Moment of inertia
M	Joint moment
M^i	Inertia joint moment
M^s	Static joint moment
P_{FSR}	Position of FSR
$P_{h\to C}$	Position difference hip to chair
R	Ground reaction force
α	Angular acceleration of joint
β	Constant for hip joint position estimation
γ	Constant for thigh angle estimation
ϵ	Angle estimation error
θ_{IMU}	Angle estimated by IMU
θ_{shank}	Shank angle
θ_{thigh}	Thigh angle
ρ_o	Radius of gyration
ω	Angular acceleration

Ⅲ. PROPOSED SYSTEM

3.1 Apparatus

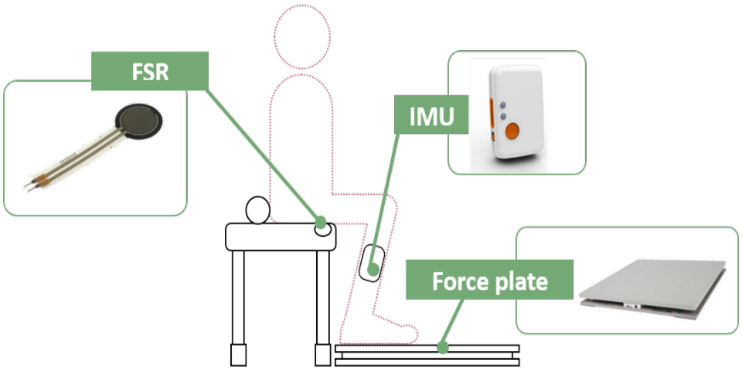


Figure 4. Apparatus of proposed system

Apparatuses for proposed system were consisted by IMU, force plate and chair with force sensing resistor (FSR). IMU measured shank angle displacement during sit to stand by using accelerometer and gyroscope. To estimate shank displacement, IMU was mounted lateral of shank. Force plate used to measure ground reaction force and center of pressure.

Figure 5. Proposed chair with FSR

The chair was used to regulate posture during sit to stand by backseat, chair height and chair position. Regulation were needed to make similar starting posture for estimation of angle. Backseat used to regulate sitting posture during replication of sit to stand [14]. Chair height were adjusted to 80% of knee height [24]. 80% of knee height of chair height was chosen, since lower height of chair made more muscle strength than higher seat height [33]. Backseat positioned on the chair and its diameter was low enough to do not conceal the markers at posterior superior iliac spine. Chair was positioned differently to each subject to make shank flexed less than 15° to the vertical.

Four FSR sensors were used to detect seat off by placing on top of chair, which to replacing force plate below chair. By using FSR, seat off was detected when voltage went to initial voltage without any loads as switch. Since, seat off was defined when buttocks lost contact with chair and detected when ground reaction force bellowed the chair went to chair weight [2].

3.2 Joint moment equation

Conventional equation to calculate joint moment was based on inverse dynamic [31]. In this equation, proximal joint affected by joint reaction force and moment of distal joint and movement of center of mass of body segment. Equation 1-4 are equation to calculate joint moment in 2-dimentional movement (For calculating ankle joint moment, M_{j-1} was zero and $r_{j-1\rightarrow c_k}$ was center of pressure to center of mass of foot). To calculated joint moment by inverse dynamic equation, all kinematics had to be considered. This made difficulty to calculate joint moment by inverse dynamic equation [32].

$$F_{j,y} = \sum_{h=1}^{k} m_h a_{com,h,y} \tag{1}$$

$$F_{j,z} = \sum_{h=1}^{k} (-m_h g + m_h a_{com,h,z}) + R_z \tag{2}$$

$$I_{o,k} = m_k (l_k \rho_{o,k})^2 \tag{3}$$

$$M_j = I_{o,k}\alpha_j + M_{j-1} - r_{j\rightarrow c_k,y}F_{j,z} + r_{j\rightarrow c_k,z}F_{j,y} - r_{j-1\rightarrow c_k,y}F_{j-1,z} + r_{j-1\rightarrow c_k,z}F_{j-1,y} \tag{4}$$

To solve the difficulty of calculating joint moment by inverse dynamic equation, Wu and Zadin [32] divided joint moment as static moment (Equation 5-7) and inertia moment (Equation 8-10). Inertia moment was moment generated at dynamic movement. To know inertia moment, all kinematics (acceleration, angular acceleration and moments of inertia of body segment) had to be considered. By contrast to the inertia moment, static moment was moment generated at static posture. Therefore, ground reaction force and joint reaction forces consisted by mass and gravitational acceleration are consisting static moment. To calculate static moment during certain movement, slow speed of movement had to be done to assume quasi-static movement.

$$F_{j,y}^{s} = R_y \tag{5}$$

$$F_{j,z}^{s} = \sum_{h=1}^{k} m_h g + R_z \tag{6}$$

$$M_j^s = M_{j-1}^s - r_{j\to c_k,y} F_{j,z}^s + r_{j\to c_k,z} F_{j,y}^s - r_{j-1\to c_k,y} F_{j-1,z}^s + r_{j-1\to c_k,z} F_{j-1,y}^s \tag{7}$$

$$F_{j,y}^{i} = \sum_{h=1}^{k} m_h a_{com,h,y} \tag{8}$$

$$F_{j,z}^{i} = \sum_{h=1}^{k} m_k a_{com,h,z} \tag{9}$$

$$M_j^i = I_{o,k}\alpha_j + M_{j-1}^i - r_{j\to c_k,y} F_{j,z}^i + r_{j\to c_k,z} F_{j,y}^i - r_{j-1\to c_k,y} F_{j-1,z}^i + r_{j-1\to c_k,z} F_{j-1,y}^i \tag{10}$$

Wu and Zadin applied these equations to calculate joint moment generated during gait motion at various speed. They made conclusions that static joint moments could estimate dynamic joint moments generated at most of walking and running speed without ankle joint moment at running.

Static moment had benefit to calculate joint moment only using joint position, center of pressure and ground reaction force. Calculating joint moment at certain single posture was possible. These made possible to decrease number of sensors to measure body movement.

3.3 Joint position estimation

Model of sit to stand position was link-segmented model consisted by two link (shank and thigh). Joint position estimation was done by the inverse kinematic model at sitting and forward kinematic model during sit to stand. Estimated segment angles were shank angle and thigh angle. These was to estimating segment angle during sit to stand on the basis of segment angle at sitting posture.

3.3.1 Sitting posture

Segment angle at sitting posture was estimated by inverse kinematics model. Hip joint position was estimated by using position hip to the chair ($P_{h \to C}$). Ankle joint position and position hip to the chair were defined by anthropometric data [31] and measured data which were marked at figure 6. Y direction of position hip to the chair couldn't measureable by its anatomical position and doesn't have anthropometric data. Therefore, it had defined value of y direction of position hip to the chair by dividing gathered experiment data to height of each subject ($P_{h \to C,y} = \beta * H$).

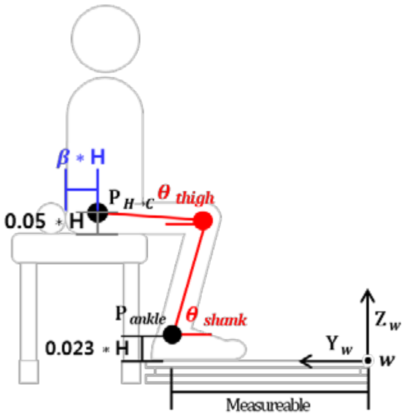


Figure 6. Controlled sitting posture and parameter to estimated (red).

3.3.2 Sit to stand motion

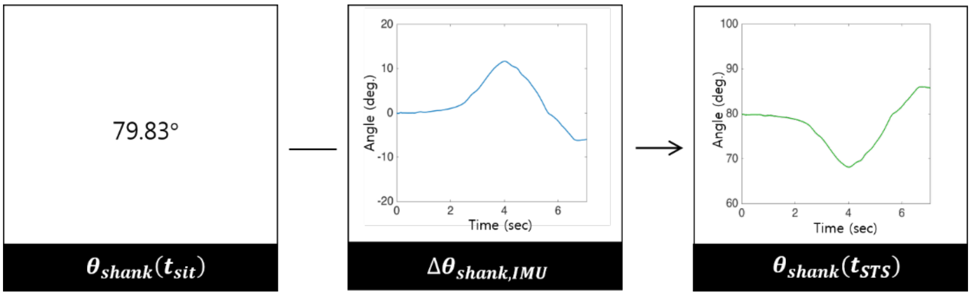


Figure 7. Estimating method to measure shank angle during sit to stand motion

Shank angle during sit to stand motion were estimated by adding shank angle displacement to estimated shank angle during sitting (Figure 7, Equation 11). Shank angle displacement during sit to stand was estimated by using

IMU. IMU was used to get accurate shank angle, because small error of shank angle estimation generated quite significant error in knee joint moment error. About 2° error of shank angle estimation generated about 10% of knee joint moment error. IMU used to calculate shank angle displacement during sit to stand motion. By using parameter of shank angle displacement during sit to stand motion, it didn't need to attach IMU precisely to get accurate absolute shank angle. It facilitated clinical friendly system.

$$\theta_{shank}(t_{STS}) \;=\; \theta_{shank}(t_{sit}) - \;\Delta\theta_{shank} \tag{11}$$

To calculate shank angle, data of accelerometer and gyroscope had used because magnetic field in clinics made distortions at magnetometer [7]. Before shank angle calculation, accelerometer used to estimate shank angle like an inclinometer [26]. After starting sit to stand motion, only gyroscope used to estimate shank angle (Equation 12-13).

$$\theta_{IMU}(t_{sit}) = tan^{-1}\left(\frac{a_y}{a_x}\right) \tag{12}$$

$$\theta_{IMU}(t_{STS}) = \theta_{IMU}(t_{sit}) + \int \omega_z(t)\, dt \tag{13}$$

$$\Delta\theta_{shank} \;=\; \theta_{IMU}(t_{STS}) - \theta_{IMU}(t_{sit}) \tag{14}$$

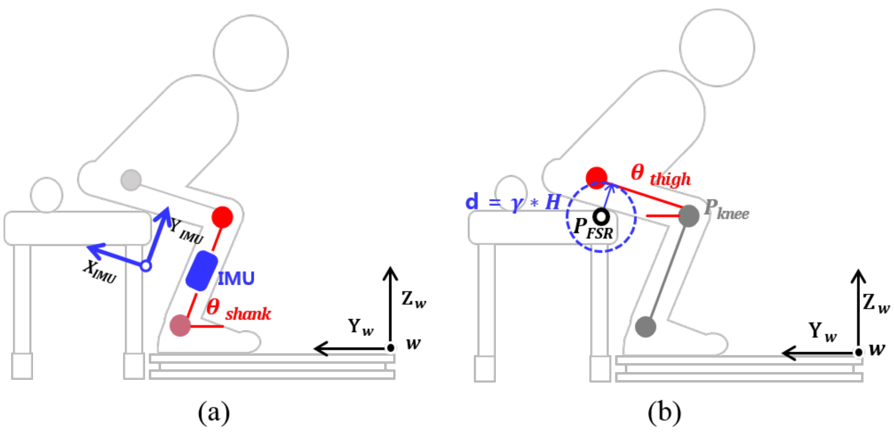


Figure 8. (a) Shank angle and (b) thigh angle estimation method during sit to stand motion

To calculate maximum hip joint moment, seat off was targeted to decrease usage of sensor mounted to the body. Near seat off, maximum joint force and moment were occurred [18, 20]. Therefore, hip joint moment at seat off could represent maximum hip joint moment.

In this paper, seat off was defined as when body lost contact with FSR. If length between thigh segment and position of FSR (d) was estimated, thigh angle could be known by slope of line which tangent to the circle centered by position of FSR and had radius of length by d. Length of d could be estimated by multiplying the constant to height of subject like estimating length between hip joint position to back seat.

After estimating length between thigh segment and position of FSR by equation 16, slope of thigh angle was calculated by using equation 17 which equation to find length between line and dot.

$$tan(\boldsymbol{\theta_{thigh}}) = \boldsymbol{c} \tag{15}$$

$$d = \gamma H \tag{16}$$

$$\frac{|c - \boldsymbol{P_{FSR,z}} - c\boldsymbol{P_{knee,y}} + \boldsymbol{P_{knee,z}}|}{\sqrt{c^2+1}} = d \tag{17}$$

Ⅳ. Experiment

Total three experiments were done. The experiments were pre-experiment and validation experiment (symmetrical and asymmetrical sit to stand). Pre-experiment was to find β, γ to do segment angle estimation which covering various strategy to do sit to stand. Symmetrical sit to stand was to validate the proposed system to healthy people, and asymmetrical sit to stand was to validate possibility of system applied at asymmetrical weight bearing during sit to stand.

4.1 Subject

Number of subjects were different by each experiment. All subjects were healthy people and information of subjects were at table 1.

Table 2. Subject information of each experiment (Average ± S.D.)

	Pre-experiment	**Symmetric sit to stand**	**Asymmetric sit to stand**
Sex	7 (4 male / 3 female)	10 (6 male / 4 female)	3 (2 male / 1 female)
Age (year)	26.40 ± 2.40	26.50 ± 2.17	27.00 ± 2.65
Height (m)	1.72 ± 0.09	1.71 ± 0.09	1.67 ± 0.08
Mass (kg)	67.60 ± 12.00	65.40 ± 11.85	63.67 27.00 ± 10.26

4.2 Experiment setting

Apparatus for proposed system and Mocap. for validation of shank angle estimation method and joint moment calculation method. Mocap. (Bonita, VICON), two force plates (OR6-7, AMTI), and chair with four FSRs and Trigno 4-Channel Footswitch Sensor (Delsys Trigno Sensor, Delsys) were used at all experiment. Sampling frequency of Mocap. was 250 Hz and that of rest devices was 1000 Hz. IMU(Shimmer 3, shimmer) were used at only validation experiment at sampling frequency of 204.8 Hz. Single IMU attached left side of lateral of shank at symmetrical sit to stand and two IMU attached both side of lateral of shank at asymmetrical sit to stand. Marker set for experiment was based on the plug in gait model for lower extremity and two additional markers attach on acromion of both side.

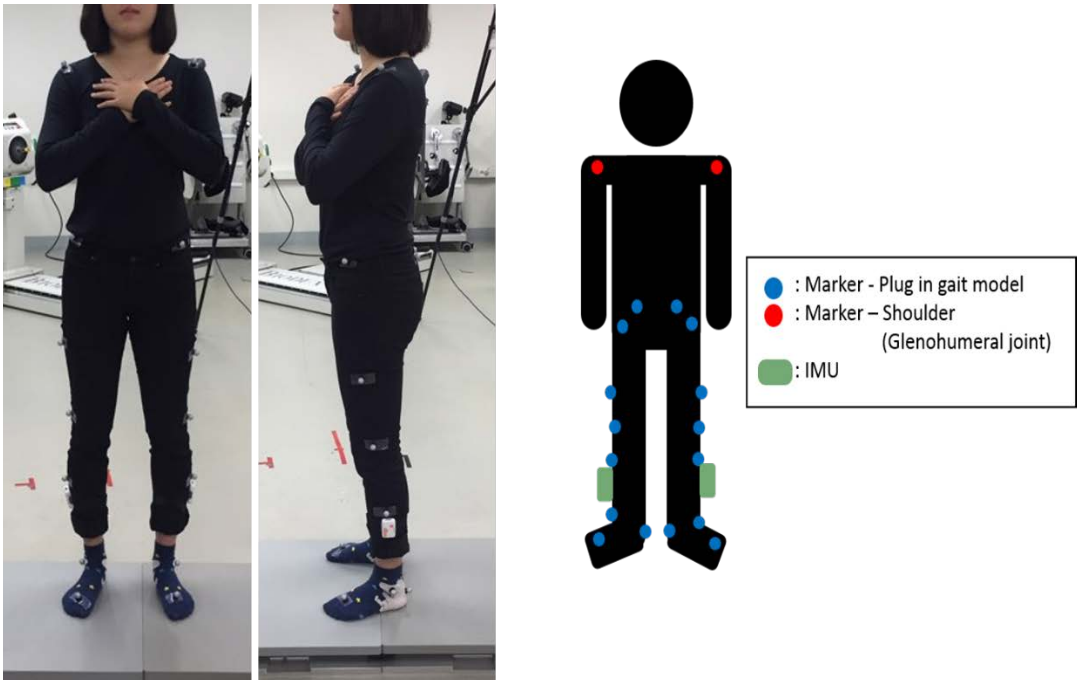


Figure 9. Markers and IMU mounted position

4.3 Experiment task

Posture to sit to stand was crossing his/her arms on the chest. Subjects were instructed to do sit to stand at slow speed and to sit on the chair regular position as possible as when replicating sit to stand. These instructions were same at pre-experiment, symmetric sit to stand experiment and asymmetric sit to stand experiment.

For the pre-experiment, height of chair and amount of flexion of upper-limb was controlled to cover various strategy to do sit to stand. Height of chair was controlled by two heights: 75 % and 80 % of knee height. At chair height of 80 % of knee height, amount of flexion of upper-limb was controlled by giving three different instructions to the subject. The instructions were flexing upper-limb more and less than usual, and natural. Sit to stand was replicated five times.

Symmetric and asymmetric sit to stand, three times sit to stand was done. Chair height were about 80% of knee height of every subject. At asymmetric task, subjects were instructed to give more weight bearing on his/her dominant side to make asymmetrical weight bearing. Two subject's dominant side was right and the other was left.

4.4 Analysis method

Data was analyzed by Nexus (1.8.5, Vicon) and Matlab (2013b, Mathworks). Nexus for maker position acquisition and filtering. Matlab used at rest analyzing.

4.4.1 Data processing

Ground reaction force and moment gathered by force plate were filtered by moving average filter which data points 25 [14]. Center of pressure was calculated by diving x-directional ground reaction moment by y-directional ground reaction force to get x direction and z-directional ground reaction force to get y-direction of center of pressure (Directions were same as figure 6 & 8). The center of axis of the force plate was translated to the world frame which place at edge of the force plate.

Trajectory data of Mocap. was filtered by 4th order butterworth filter cut off frequency as 2Hz. For the IMU, acceleration from accelerometer was filtered by moving average filter of 21 frames. For the gyroscope, angular acceleration data were not filtered and average values of yaw during sitting was subtracted to decrease drift error [27].

4.4.2 Sit to stand event detection

There was various way to detect event of the sit to stand. Mostly, movement of shoulder was considered as start of sit to stand motion to shoulder flexion [21]. In this system, position of shoulder joint wasn't gathered during the motion. Therefore, sit to stand event was detected by the z-directional ground reaction force based as the study of Agrawal et. al. [2]

$$\left|\frac{dR_z}{dt}\right| \geq 0.05\left(\frac{dR_z}{dt}\right)_{MAX} \tag{18}$$

$$\frac{dR_z}{dt} = minimum \tag{19}$$

Start of sit to stand motion was detected by the equation 18. Agrawal et. al. used not absolute value as to decline of the z-directional ground reaction force happened before increase of ground reaction force by transferring center of mass below the chair to the below of the foot. This happened at fast and natural sit to stand motion. In our system, subjects were done sit to stand motion at slow speed. The decline of the vertical ground did not always happen. Therefore, equation 14 used for the experiment. Deceleration was detected as same as the Agrawal et. al. as equation 19.

Agrawal et. al. placed the both side of the foot at single force plate, although left side of foot was placed on the force plate in this study. Therefore, whole body weight couldn't measure like Agrawal et. al. used to detect end of sit to stand motion. Healthy subjects were standing up asymmetric [25]. Detection when z-directional ground reaction force when it went to the half of body weight was hard to detect. Therefore, only z-directional ground reaction force in steady result of boundary within 1% of body weight in 0.5sec was used.

4.4.3 Comparing joint moment

Table 3. Features of joint moment calculation method

	Golden standard (GS)	**Proposed system (PS)**
Joint moment equation	Inverse dynamic equation	Static moment
Plane	Sagittal plane	
Segment length & mass	Anthropometry	
Joint angle	Mocap.	Estimated

Comparing joint moment was done by joint moment calculated by golden standard and proposed system. Golden standard and proposed system had difference of equation to calculate joint moment and method to get joint moment as shown at table 2. Both system had same approximation of moving plane as sagittal plane and segment length and mass used anthropometric data. Calculated joint moments were normalized by subject's weight.

To see accuracy of joint moment, angle estimation error, RMSE, and RMSPE had calculated. Angle estimation error was seen shank angle thigh angle estimation error compared with golden standard as equation 16. RMSE calculated in shank angle estimation and ankle and knee joint moment during sit to stand motion.

$$\epsilon_j = \theta_{GS,k} - \theta_{PS,k} \tag{20}$$

$$RMSPE = \sqrt{\frac{1}{f}\sum_{n=1}^{f}\left(\frac{\theta_{GS,n}-\theta_{PS,n}}{\theta_{GS,n}}\right)^2} \tag{21}$$

Hip joint moment wasn't calculated RMSE during sit to stand, since thigh angle estimated at only seat off. RMSPE was calculated by equation 21. Joint moment at instance of maximum joint moment of golden standard was compared to see RMSPE. At hip joint moment, maximum joint moment of golden standard was compared with hip joint moment at seat off of proposed system. Boundary of accuracy was 20% of error as previous study. Linear relationship had seen by correlation coefficient during sit to stand at ankle and knee joint moment.

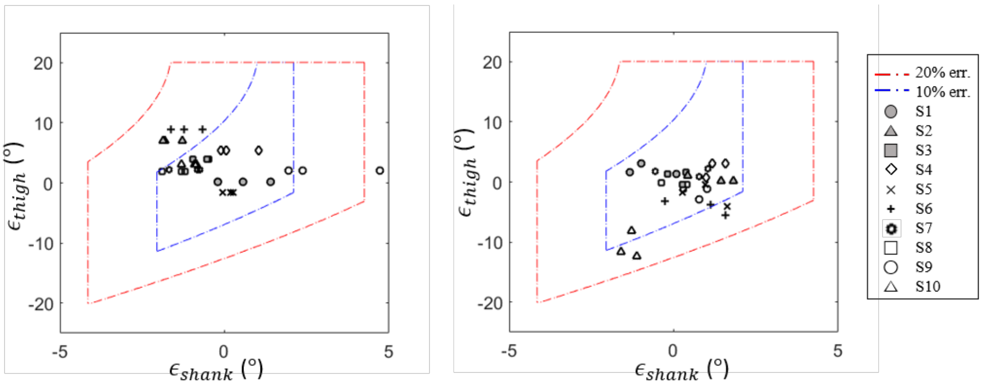
Ⅴ. RESULT

5.1 Pre-experiment

Average values of length between hip joint and back seat in y-direction was 0.147 ± 0.016 m. To define β, length between hip joint to back seat in y-direction was divided by each subject's height. The result of divided result was 0.086 ± 0.008. β was defined as 0.085 which was similar values of 0.086. For the γ, length between thigh segment and position of FSR was divided by each subject's height like β. It's value was 0.06 ± 0.008. γ was defined as 0.06.

5.2 Symmetrical sit to stand

RMS of time difference between timing of maximum joint moment to timing of seat off were 1.97 second for ankle joint, 0.70 second for knee joint and 0.34 second for hip joint. The timings percentage to time of sit to stand were 41.8% for ankle joint, 12.6% for knee joint and 5.64% for hip joint. Among three joint, timing of maximum hip joint moment was closest to timing of seat off among joints of lower extremity.



(a) Sitting (b) Seat off

Figure 10. Angle estimation error at sitting and seat off

The figure 10 (a) and (b) were result of angle estimation error. Dotted line represented how much angle estimation error generated 10 % and 20 % of joint moment error. Knee joint moment error effected by shank angle estimation error and hip joint moment error effected by shank angle and thigh angle estimation error. Thigh angle estimation error bounded not to over 20°. Blue represented 10 % error and red represented 20 % error. The error boundary could changeable by different ground reaction force and segment angle. As seen figure 10 (a) and (b), most of the subjects were in 20% error boundary.

Table 4. RMSE of shank angle between estimated shank angle and Mocap.

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Mean ± S.D. (°)	1.83 ±0.84	3.00 ±0.33	3.10 ±0.08	1.90 ±0.42	1.15 ±0.56	0.99 ±0.12	2.18 ±1.21	3.05 ±0.33	4.01 ±0.41	1.90 ±0.92

Table 3 presented RMSE values of shank angle between estimated shank angle and Mocap. during sit to stand. Mean of RMSE values were similar to or less than 4°. Table 4 presented RMSE and correlation coefficient of ankle and knee joint moment. Mean value of RMSE were less than 0.1 Nm/kg in ankle and knee joint moment. Correlation coefficients were similar to the 1.

Table 5. RMSE of joint moment and correlation coefficient of ankle and knee (Mean ± S.D.)

	Ankle joint moment	**Knee joint moment**
RMSE (Nm/kg)	0.02 ± 0.07	0.07 ± 0.04
Correlation coefficient	1.00 ± 0.00	0.98 ± 0.01

Table 6. Maximum joint moment of GS and PS (Mean ± S.D.)

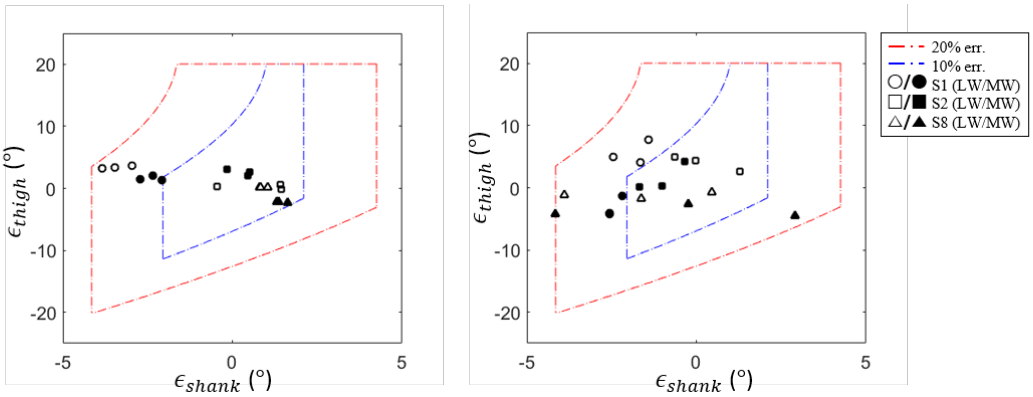
	Ankle joint moment	**Knee joint moment**	**Hip joint moment**
GS (Nm/kg)	0.44 ± 0.16	0.66 ± 0.17	1.11 ± 0.24
PS (Nm/kg)	0.43 ± 0.16	0.69 ± 0.18	1.09 ± 0.26

Table 7. RMSPE of maximum joint moment

	Ankle joint moment	Knee joint moment	Hip joint moment
RMSPE (%)	6.56	9.83	12.00

Table 5 presented maximum ankle, knee and hip joint moment of GS and PS. Table 6 presented RMSPE of maximum ankle, knee and hip joint moment. The values of table 5 and table 6 were different. Since, RMSPE was root mean square of each trial's percentage error and values of table 5 was average of every trials. Therefore, individuality was decreased. Ankle, knee and hip joint moment's RMSPE were less than 20%. However, three trials among whole trials were over 20% of error boundary when seeing trials individually.

5.3 Asymmetrical sit to stand



(a) Sitting (b) Seat off

Figure 11. Angle estimation error at sitting and seat off

Table 8. RMSE of shank angle between estimated and Mocap.

	S1		S2		S8	
	LW	MW	LW	MW	LW	MW
Mean ± S.D. (°)	1.83 ±0.84	3.00 ±0.33	3.10 ±0.08	1.90 ±0.42	1.15 ±0.56	0.99 ±0.12

Weight distribution occurred by asymmetrical movement, less weighted (LW) side shown which was non-dominant side. Conversely, more weighted (MW) side occurred at dominant side. Figure 11 (a) and (b) represented angle estimation error at sitting and seat off. Most of shank angle thigh angle estimation error were in the boundary of 20% of error. Comparing with figure 10, shank angle estimation error during sitting were more likely to near 20% error boundary. RMSE of shank angle estimation were less than 4°. There were not significantly difference between LW and MW side.

RMSE of joint moment was less than 0.1Nm/kg for ankle and knee joint moment. Correlation coefficient were all over 0.95. Comparing ankle and knee joint, knee joint moment had larger joint moment error and lower correlation coefficient than ankle joint moment.

Table 9. RMSE of joint moment and correlation coefficient of ankle and knee (Mean ± S.D.)

	Ankle joint moment		**Knee joint moment**	
	LW	**MW**	**LW**	**MW**
RMSE (Nm/kg)	0.02 ± 0.01	0.03 ± 0.01	0.08 ± 0.03	0.07 ± 0.06
Correlation coefficient	1.00 ± 0.00	1.00 ± 0.00	0.95 ± 0.06	0.97 ± 0.03

Table 10. Maximum joint moment of GS and PS (Mean ± S.D.)

	Ankle joint moment		**Knee joint moment**		**Hip joint moment**	
	LW	**MW**	**LW**	**MW**	**MW**	**LW**
GS (Nm/kg)	0.41 ± 0.09	0.55 ± 0.12	0.34 ± 0.21	0.86 ± 0.18	0.62 ± 0.14	1.36 ± 0.31
PS (Nm/kg)	0.39 ± 0.09	0.58 ± 0.10	0.33 ± 0.18	0.78 ± 0.24	0.59 ± 0.20	1.28 ± 0.36

Table 11. RMSPE of maximum joint moment

	Ankle joint moment		**Knee joint moment**		**Hip joint moment**	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
RMSPE (%)	5.07	7.95	15.15	14.18	10.40	10.72

Maximum ankle, knee and hip joint moment of LW and MW weren’t similar. Maximum ankle, knee and hip joint moment of MW had larger values than LW (table 9), since LW side ground reaction force were smaller than MW side. Relatively, small difference shown at ankle joint moment. RMSPE of maximum joint moment were less than 20% for whole joint and less weighted and more weighted side. However, three trials among whole trials were over 20% of error boundary when seeing trials individually and separately by LW and MW side.

Ⅵ. DISCUSSION

6.1 Comparing with conventional study

RMSE and correlation coefficient were compared with the Kodama [13]. Hip joint moment wasn't compared with Kodama, since hip joint moment was calculated at seat off only. RMS error during sit to stand for ankle and knee joint was smaller than the Kodama. Moreover, correlation coefficient was larger than Kodama. This result had been shown because of difference in joint moment calculation method.

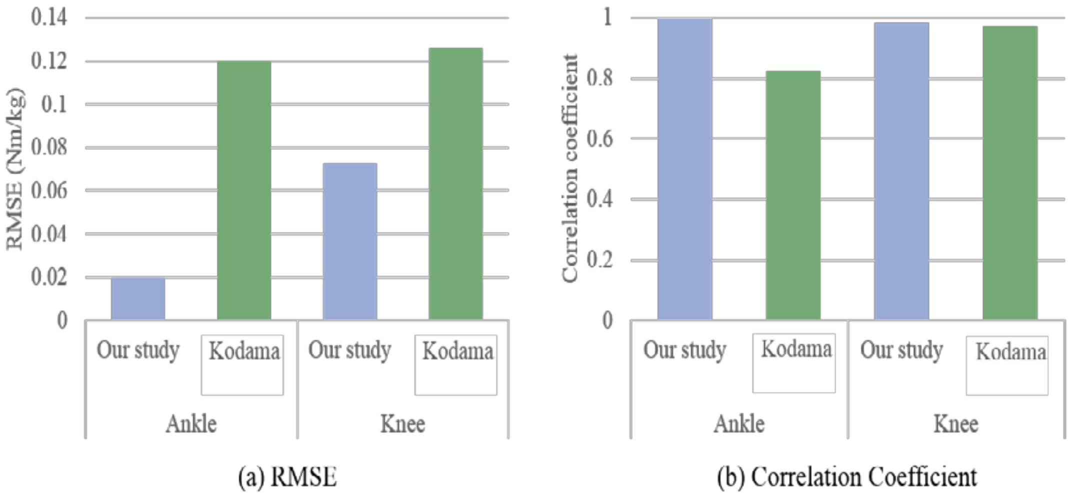
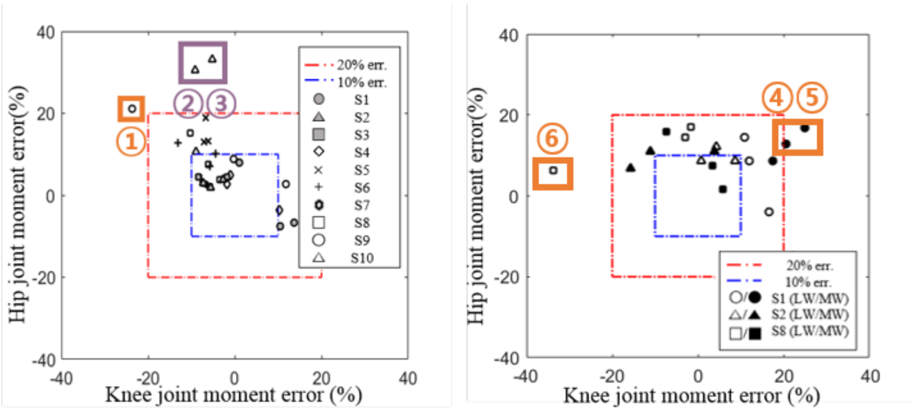


Figure 12. RMSE and Correlation coefficient of Ankle and knee joint moment compared with our study and Kodama.

Human body was estimated as link-segment model. Joint moments were calculated progressively from ankle to head which was bottom-up method or head to ankle which was top-down method. Therefore, bottom-up method had largest error at hip and top-down method had largest error at ankle joint for lower extremity. In our study, joint moment was calculated by bottom-up method. Top-down method was used at Kodama method. Kodama had largest error at ankle joint moment and our study had smallest error at ankle joint moment. In aspect of diagnosis of muscle strength by using joint moment, our method was more suitable than Kodama.

6.2 Cause and method to improvement of maximum joint moment percentage error over 20%

Figure 13. percentage of knee and hip joint maximum joint moment error for each trials. Total six trials over 20% percentage error. These six trials divided into two groups by cause of error. First cause of error was initial angle error which three trials in orange rectangle. Second cause of error was generated by unexpected sit to stand movement which two trials in purple rectangle. were error generated by initial angle error and trials in purple square were generated by unexpected sit to stand movement.



(a) Symmetrical sit to stand (b) Asymmetrical sit to stand

Figure 13. Knee and hip joint moment error relative to maximum joint moment of GS. Symmetrical sit to stand result was at (a). Asymmetrical sit to stand result was at (b).

Initial angle estimation error in shank angle was first cause of error. Table . was shank angle estimation error at sitting and seat off. Two values were similar with small error about 0.25°. Majority shank angle estimation error were effected by initial shank angle estimation error. To decrease error, β needs to be changed to improve individuality of each person.

Table 12. Shank angle estimation error at sitting and seat off

	①	④	⑤	⑥
t_{sit} **(deg.)**	4.78	-2.79	-2.37	1.74
$t_{seat\ off}$ **(deg.)**	5.08	-2.99	-2.59	1.25

Unexpected sit to stand movement occurred during sit to stand motion which affecting thigh movement. The unexpected movement was gathering thigh during sit to stand to generate enough strength to sit to stand. Gathering thigh was movement of frontal axis which was x axis in world frame in our study. At unexpected movement, x directional ground reaction force at seat off was over double of x directional ground reaction force at standing. By contrast, x directional ground reaction force at seat off was about half of x directional ground reaction force at standing at expected movement. Therefore, the unexpected movement which gathering thigh during sit to stand generated more x directional movement.

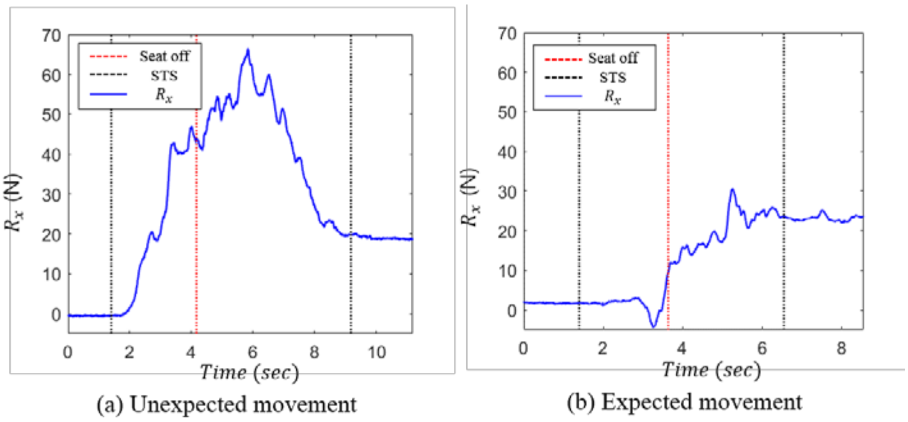


Figure 14. X directional ground reaction force during sit to stand of unexpected movement, (a) and expected movement, (b). Black dashed line represented start and end of sit to stand motion (First : start, Second : end) .

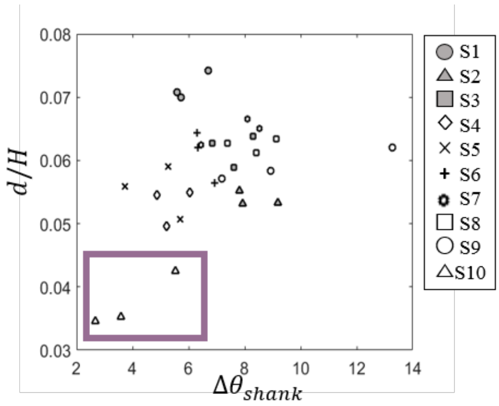


Figure 15. Result of length between FSR position to thigh segment divided by height of each subjects. Purple boxed trials were about trials done by unexpected movement.

Gathering thigh during sit to stand makes thigh angle displacement between sitting and seat off about 1° to 2°.

Also, shank angle displacement was about 2° to 3°. Comparing with other subjects, shank angle displacement was smaller than other subjects (Figure 15). Moreover, a little displacement in thigh angle made thigh thickness estimation of γ as 0.06 not worked. Figure 15 presented result of length between FSR position to thigh segment divided by height of each subjects. The values are smaller than other subjects which was average as 0.037. To decrease error, γ needed to be modified.

Estimation length between hip joint position to the back seat of chair could be modified to consider individuality of each person. Two expected method were existed. First method was directly measuring length between greater trochanter to back. Length between hip joint position to back seat and great trochanter to backseat had difference. Mocap. result had larger than measured one. Since, hip joint position got by Mocap. was estimated by equation about relationship between ASIS, PSIS and leg length [8]. Anatomical position and the estimation might be not same. Therefore, measuring length between greater trochanter to back wasn't suitable to present hip joint position estimated by relationship between ASIS, PSIS and leg length.

Table 13. Length between hip joint position or great trochanter to backseat.

	Mocap. (m)	**Measured (m)**
S1	0.145 $\pm$ 0.005	0.127 $\pm$ 0.011
S6	0.149 $\pm$ 0.003	0.129 $\pm$ 0.009
S7	0.182 $\pm$0.002	0.139 $\pm$ 0.006

Second method was trend line between value which multiplying mass and height or BMI and length between hip joint position to the back seat of chair. Trend line of linear and quadratic equation had been seen and made by experiment result of pre-experiment. Trend line of BMI had larger error than that of multiplied mass and height.

Expected solution for modifying d was applying different γ by different condition and equation relationship between shank angle d placement and d. First, different condition about x-directional ground reaction force and shank angle displacement which measured by IMU. At unexpected sit to stand motion, x-directional ground reaction force at seat off was over double of the reaction force at static standing, but x-directional ground reaction force at expected sit to stand was not. Therefore, different γ could applied like figure 16. The other method was trend line between d and shank angle displacement. First method had smaller thigh angle error and higher r^2

than second method. Therefore, method 1 was better method to represent the model.

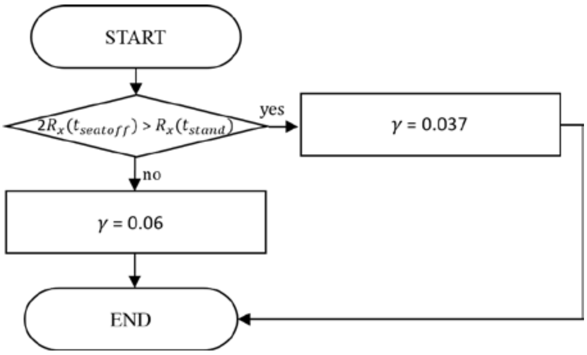


Figure 16. Flowchart of method 1

Joint moment maximum errors which modified method to estimate were compared with proposed estimated method. Maximum joint moment percentage error which other 20% decreased to three which was half of proposed system when using trend line of quadratic expression made by multiplying mass and height and length between hip joint position and back seat. Estimating joint position could be replaceable proposed system.

Ⅵ. CONCLUSION

The purpose of study was proposing clinical friendly system to measure maximum joint moment during sit to stand. To do, proposed system had one or two sensors mounted to the shank and sensors mounted roughly to be body to use easily. Also, possibility of joint moment at asymmetrical sit to stand had been seen. Joint moment estimation was more accurate and representative to the golden standard at ankle and knee joint moments than comparing with existed study. Most of results were in the range of 20% of error which targeted in symmetrical and asymmetrical sit to stand motion.

Although majority of results in expected error of 20%. Estimation method wasn't estimated whole task. Possible method to improve had applied and number of trials over 20% of error in maximum joint moment was decreased. Still, errors over 20% existed and needed to targeted error to 10% to make more accurate system to estimate. System had only validated at healthy people which different to targeted people to use system. Estimation method needed to be improved to cover individuality of various mass, height and way to sit to stand. Validation of proposed system to elderly people or patient to be used at clinics.

Appendix

Appendix 1 Individual result

Appendix 1.1 Symmetric sit to stand

Appendix 1.1.1 Angle estimation

Angle estimation error for each subjects were in table 13-17. During sitting posture, S9 had largest error. Most of shank angle estimation error during sitting and shank angle displacement error were within 2 degrees in RMSE. S9 shown largest error among subject also at shank angle error at seat off. Shank angle displacement of S9 was 0.31° of RMSE. Therefore, S9 shank angle estimation error derived by shank angle error during sitting.

Table 14. Estimated shank angle error during sitting

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	79.83	78.92	79.20	81.13	77.49	76.52	78.46	81.41	77.21	79.59
$\boldsymbol{\theta_{GS}}$ **(deg.)**	80.40 $\pm$0.80	77.26 $\pm$0.33	78.53 $\pm$0.26	80.56 $\pm$0.63	77.63 $\pm$0.15	74.96 $\pm$0.48	77.38 $\pm$0.53	79.94 $\pm$0.36	79.61 $\pm$0.46	78.60 $\pm$0.25
RMSE (deg.)	0.88	1.68	0.70	0.60	0.19	1.23	1.16	1.50	2.43	1.04

Table 15. Shank angle displacement : sitting to seat off

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	6.01 $\pm$0.60	6.66 $\pm$0.76	6.93 $\pm$0.68	4.13 $\pm$0.42	4.51 $\pm$0.59	4.97 $\pm$0.50	6.61 $\pm$1.27	6.84 $\pm$0.91	11.93 $\pm$3.12	5.41 $\pm$1.44
$\boldsymbol{\theta_{GS}}$ **(deg.)**	7.36 $\pm$0.80	5.42 $\pm$0.19	6.77 $\pm$0.68	4.45 $\pm$0.42	4.09 $\pm$0.59	4.56 $\pm$0.50	6.19 $\pm$1.27	6.74 $\pm$0.91	11.85 $\pm$3.18	3.96 $\pm$1.40
RMSE (deg.)	1.36	1.35	0.18	0.46	0.44	0.61	0.5	0.11	0.31	1.46

Table 16. Shank angle error at seat off

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	73.82 ±0.60	72.27 ±0.76	72.28 ±0.68	77.00 ±0.42	72.98 ±0.59	71.55 ±0.50	71.85 ±1.27	74.57 ±0.91	65.28 ±3.12	74.18 ±1.44
$\boldsymbol{\theta_{GS}}$ **(deg.)**	73.06 ±1.02	71.84 ±0.52	71.77 ±0.46	77.00 ±0.79	73.54 ±0.43	70.80 ±0.75	71.19 ±1.71	73.20 ±1.25	67.76 ±3.31	74.61 ±1.58
RMSE (deg.)	0.96	0.72	0.56	0.54	0.59	1.09	0.96	1.40	2.55	0.45

Amount of error of thigh angle at seat off was larger than that of shank angle at seat off. Especially, the error of thigh angle was over 10° in RMSE which made by higher values of thigh angle estimated by proposed system.

Table 17. Thigh angle error at seat off

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	25.27 ±0.14	15.65 ±0.08	20.9 ±0.06	17.78 ±0.02	28.34 ±0.19	11.73 ±0.07	19.56 ±0.02	23.50 ±0.18	21.12 ±0.12	20.84 ±0.18
$\boldsymbol{\theta_{GS}}$ **(deg.)**	29.1 ±1.24	18.55 ±0.19	24.15 ±0.76	21.18 ±0.63	26.22 ±1.81	7.57 ±1.14	21.13 ±0.66	22.96 ±0.55	21.54 ±2.29	10.64 ±2.92
RMSE (deg.)	3.98	2.95	3.32	3.45	2.60	4.28	1.67	0.70	1.83	10.51

Appendix 1.1.2 Joint moment

Most of RMSE of ankle and knee joint moment during sit to stand motion (table 17) was smaller or same to 0.1Nm/kg. Among them, RMSE of knee joint moment of S9 was largest. Largest error of S9 could be derived by shank angle estimation error during sitting posture.

Maximum joint moment of lower extremity was shown at figure 17-19. Ankle joint had shown smallest value among lower extremity. Average values of joint moment which three times of sit to stand motion had shown similar values between GS and PS.

Table 18. RMSE of joint moment and correlation coefficient of ankle and knee (Mean ± S.D.)

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Joint moment										
Ankle (Nm/kg)	0.00 ±0.00	0.01 ±0.00	0.02 ±0.00	0.01 ±0.00	0.01 ±0.00	0.05 ±0.01	0.02 ±0.00	0.02 ±0.00	0.03 ±0.00	0.01 ±0.01
Knee (Nm/kg)	0.05 ±0.03	0.09 ±0.01	0.10 ±0.00	0.07 ±0.01	0.02 ±0.00	0.04 ±0.01	0.07 ±0.04	0.08 ±0.01	0.14 ±0.01	0.07 ±0.03
Correlation coefficient										
Ankle	1.00 ±0.00	1.00 ±0.00	1.00 ±0.00	1.00 ±0.00	1.00 ±0.00	0.99 ±0.01	0.99 ±0.01	1.00 ±0.00	1.00 ±0.00	1.00 ±0.00
Knee	0.99 ±0.00	0.97 ±0.01	0.97 ±0.01	0.98 ±0.01	1.00 ±0.00	1.00 ±0.00	0.98 ±0.01	0.96 ±0.01	0.98 ±0.01	0.98 ±0.00

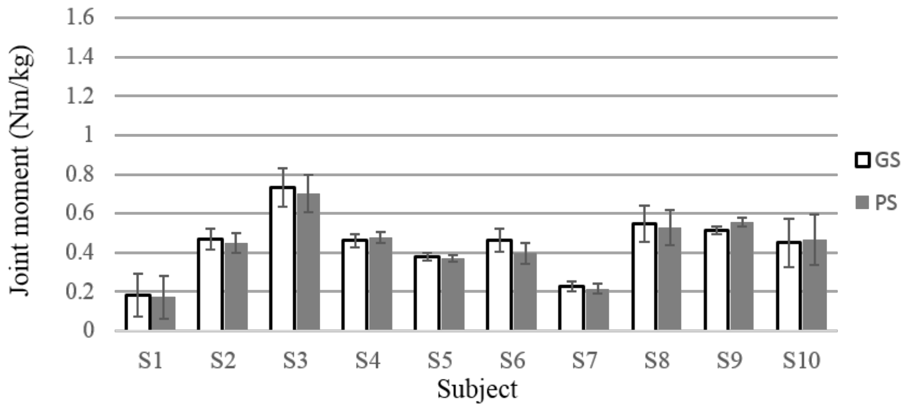


Figure 17. Maximum ankle joint moment

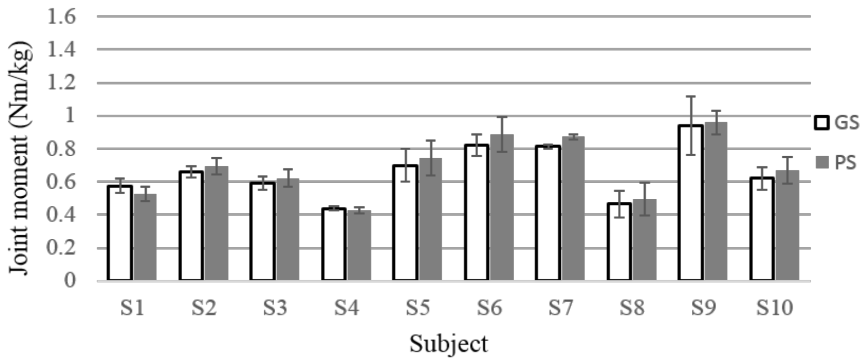


Figure 18. Maximum knee joint moment

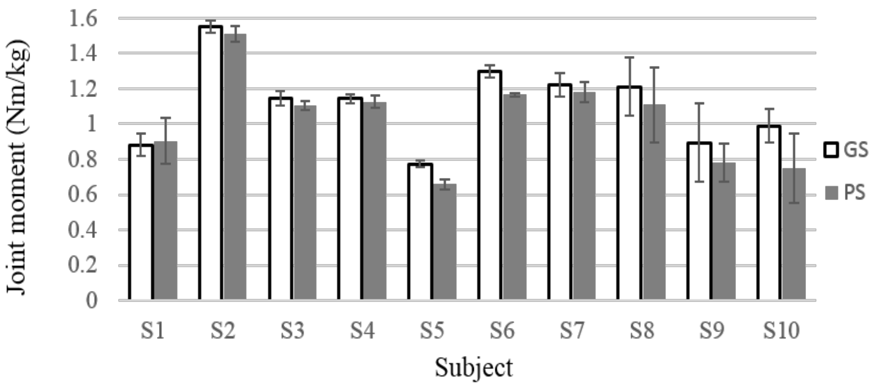


Figure 19. Maximum hip joint moment

Maximum joint moment percentage error of average of three trials was less than 20%, except S10. These tendencies had shown at RMSPE of three trials for each subject (table 19). Percentage error of knee joint moment between mean and RMSPE was largely different in the S9. At the mean of three trials, percentage error was -1.9%. At the RMSPE, knee joint moment error was 15.23% which 13 times larger than previous. Averaging joint moment loosing variability of joint moment between trials, therefore, error had decreased. Knee joint moment of GS of S9 had larger standard deviation compared to the S9.

Table 19. Maximum joint moment error of three average trials

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Maximum joint moment error										
Ankle (Nm/kg)	0.009	0.017	0.029	-0.015	0.006	0.069	0.014	0.020	-0.041	-0.015
Knee (Nm/kg)	0.049	-0.035	-0.031	0.011	-0.046	-0.066	-0.060	-0.032	-0.018	-0.049
Hip (Nm/kg)	-0.022	0.045	0.042	0.016	0.117	0.130	0.042	0.102	0.111	0.237
Maximum joint moment percentage error										
Ankle (%)	4.8	3.7	4.0	-3.3	1.5	14.7	6.1	3.6	-7.9	-3.4
Knee (%)	8.6	-5.3	-5.3	2.6	-6.6	-8.0	-7.4	-6.9	-1.9	-7.9
Hip (%)	-2.5	2.9	3.7	1.4	15.1	10.1	3.4	8.4	12.4	24.0

Table 20. RMSPE of ankle, knee and hip maximum joint moment

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Ankle (%)	7.55	3.74	4.03	3.51	2.07	15.01	6.24	3.66	7.97	3.64
Knee (%)	10.03	5.53	5.95	6.03	6.62	8.64	7.44	7.13	15.23	8.03
Hip (%)	7.45	2.99	3.84	3.83	15.31	10.27	3.48	10.04	13.28	26.69

Appendix 1.2 Asymmetric sit to stand

Appendix 1.2.1 Angle estimation

Among three subjects, S1 had largest error. At seat off, shank angle estimation error of S1 during sitting was decreased by shank angle displacement estimation error which had larger values than GS. However, shank angle error at seat off of S1 was largest among three subjects. RMSE of shank angle error at seat off was smaller than 2.5°.

Shank angle between LW and MW was similar at the seat off about 1° error. For the thigh angle, difference between LW and MW was different by subject. S1 and S8 had larger thigh angle at LW. S2 had similar thigh angle between LW and MW. Thigh angle estimation method at seat off estimated similar between LW and MW. Estimation method was needed to be improved to variable movement to do sit to stand.

Table 21. Estimated shank angle error during sitting

	S1		**S2**		**S8**	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	79.66		74.10		78.69	
$\boldsymbol{\theta_{GS}}$ **(deg.)**	76.24 $\pm$0.44	77.28 $\pm$0.32	74.99 $\pm$0.12	75.54 $\pm$0.16	78.96 $\pm$1.08	79.50 $\pm$0.37
RMSE (deg.)	3.44	2.40	0.89	1.44	1.20	0.41

Table 22. Shank angle displacement : sitting to seat off

	S1		S2		S8	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	6.23 $\pm$0.35	4.30 $\pm$0.46	3.56 $\pm$2.41	5.60 $\pm$0.58	5.05 $\pm$0.73	4.26 $\pm$2.04
$\boldsymbol{\theta_{GS}}$ **(deg.)**	4.92 $\pm$0.48	4.36 $\pm$0.52	4.28 $\pm$0.92	5.68 $\pm$1.31	4.28 $\pm$0.69	4.33 $\pm$1.87
RMSE (deg.)	1.36	0.32	1.62	1.31	0.79	0.16

Table 23. Shank angle error at seat off

	S1		S2		S8	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	73.44 $\pm$0.35	75.37 $\pm$0.61	70.55 $\pm$2.41	68.50 $\pm$0.58	73.64 $\pm$0.73	74.43 $\pm$2.04
$\boldsymbol{\theta_{GS}}$ **(deg.)**	71.33 $\pm$0.24	72.92 $\pm$0.38	70.71 $\pm$1.03	69.86 $\pm$1.34	75.22 $\pm$0.41	74.63 $\pm$2.05
RMSE (deg.)	2.11	2.45	1.37	1.87	1.83	0.36

Table 24. Thigh angle error at seat off

	S1		S2		S8	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
$\boldsymbol{\theta_{PS}}$ **(deg.)**	30.02 $\pm$0.10	30.54 $\pm$0.13	33.13 $\pm$0.33	32.88 $\pm$0.37	27.90 $\pm$0.39	27.39 $\pm$0.26
$\boldsymbol{\theta_{GS}}$ **(deg.)**	35.67 $\pm$1.83	27.21 $\pm$1.78	30.79 $\pm$1.78	29.04 $\pm$0.64	31.00 $\pm$1.93	28.96 $\pm$2.46
RMSE (deg.)	5.85	3.64	2.65	3.93	3.40	2.42

Appendix 1.2.2 Joint moment

Joint moment error between GS and PS was smaller than 0.15 Nm/kg which was higher error than symmetric movement. The higher error might be generated by MW had higher joint moment error than joint moment generated by symmetric sit to stand, although error ratio was similar. Joint moment generated at MW side had higher values than that of symmetric by higher ground reaction force. For S8, RMSE of knee joint moment at MW was 0.14 Nm/kg and correlation coefficient was smallest among three subjects, which less than 0.9. Therefore, error was generated by shank angle displacement estimation.

Table 25. RMSE of joint moment and correlation coefficient of ankle and knee (Mean $\pm$ S.D.)

	S1		**S2**		**S8**	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
Joint moment						
Ankle (Nm/kg)	0.01$\pm$0.00	0.01$\pm$0.00	0.02$\pm$0.00	0.04$\pm$0.00	0.02$\pm$0.00	0.03$\pm$0.00
Knee (Nm/kg)	0.10$\pm$0.02	0.10$\pm$0.00	0.02$\pm$0.01	0.14$\pm$0.02	0.14$\pm$0.07	0.10$\pm$0.05
Correlation coefficient						
Ankle	1.00$\pm$0.00	1.00$\pm$0.00	1.00$\pm$0.00	1.00$\pm$0.00	1.00$\pm$0.00	0.99$\pm$0.00
Knee	0.98$\pm$0.01	0.99$\pm$0.00	0.98$\pm$0.01	0.99$\pm$0.01	0.88$\pm$0.09	0.98$\pm$0.01

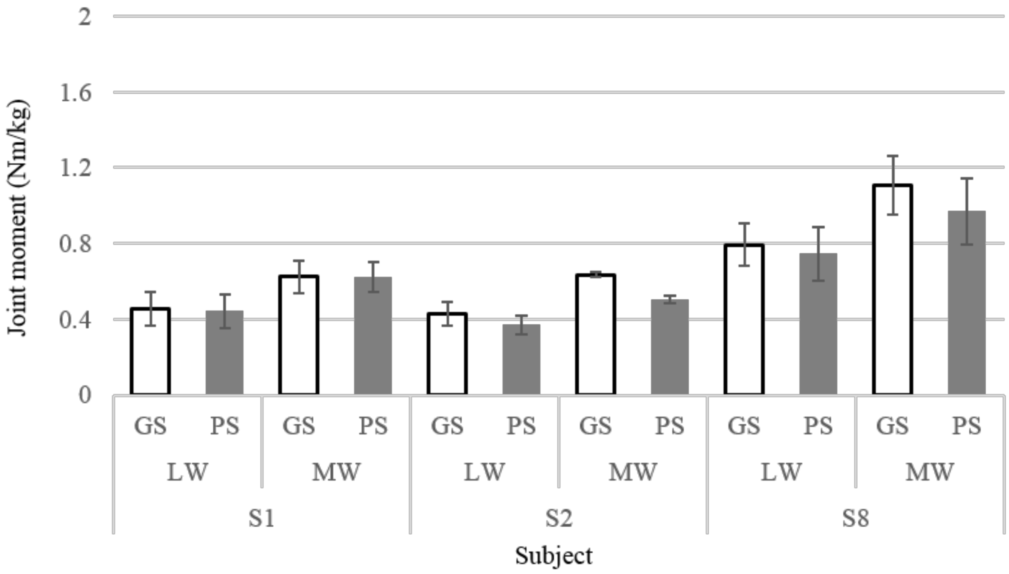


Figure 20. Maximum ankle joint moment

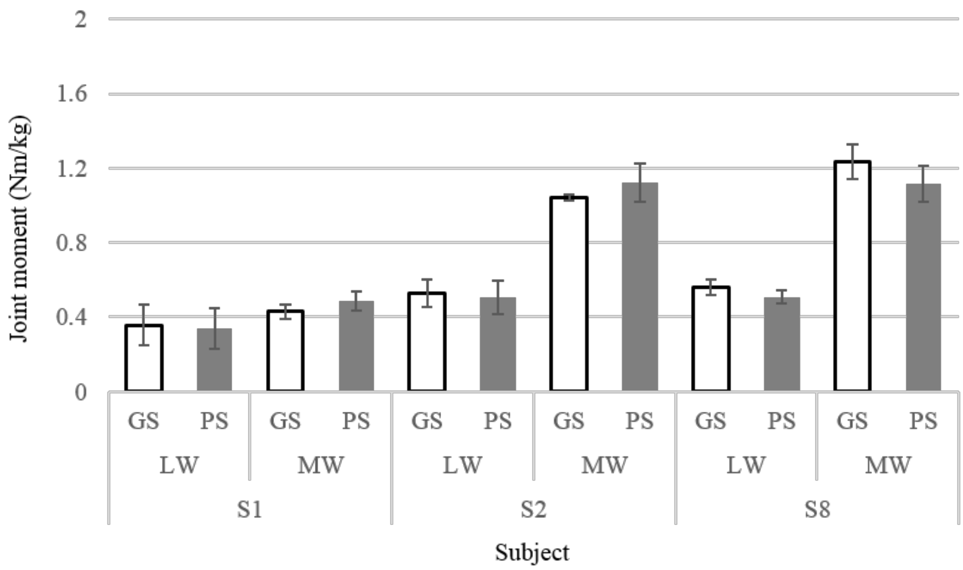


Figure 21. Maximum knee joint moment

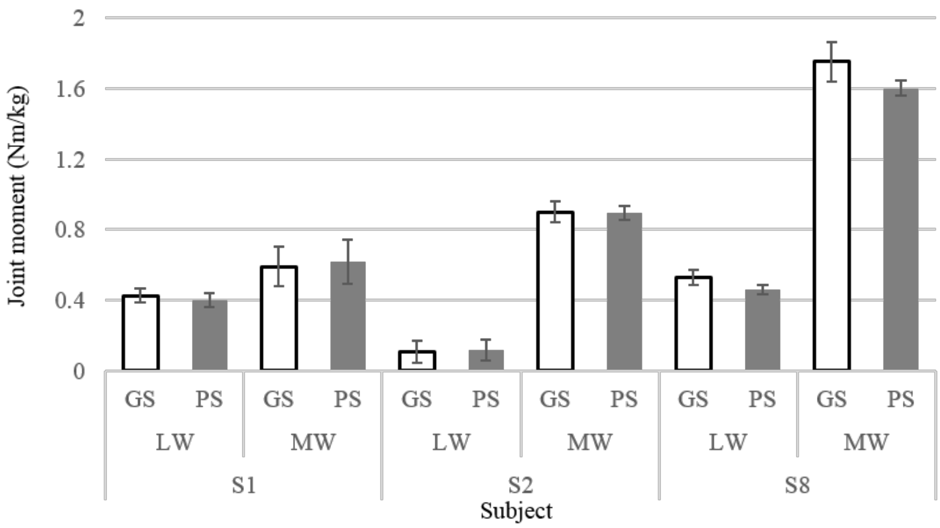


Figure 22. Maximum hip joint moment

Maximum joint moment percentage error was less than 20% of most subject and weighted side. At maximum knee joint moment percentage error of MW of S1, percentage error was mover 20%. Shank angle estimation error during sitting was effecting the error.

Figure 26. Maximum joint moment error of three average trials

	S1		**S2**		**S8**	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
Maximum joint moment error						
Ankle (Nm/kg)	0.014	-0.001	0.017	-0.056	0.027	-0.027
Knee (Nm/kg)	-0.057	-0.133	-0.023	0.080	-0.012	0.90
Hip (Nm/kg)	0.048	0.138	0.055	0.118	0.067	0.151
Maximum joint moment percentage error						
Ankle (%)	3.02	-0.11	4.77	-12.91	6.25	-4.66
Knee (%)	13.44	21.01	4.29	-7.64	-11.21	0.90
Hip (%)	6.06	12.44	9.78	9.59	12.75	8.62

Like maximum joint moment error of three average trial, knee joint moment RMSPE of S1 was over 20%. Knee joint moment percentage error of S8 was similar to 20% error. A trial was higher than 30%. This generated high error at RMSPE.

Table 27. RMSPE of ankle, knee and hip maximum joint moment

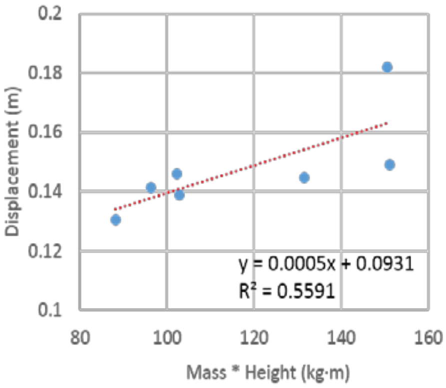
	S1		**S2**		**S8**	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
Ankle (%)	3.19	0.97	5.24	12.90	6.29	4.70
Knee (%)	13.45	21.21	5.67	11.32	19.56	5.72
Hip (%)	9.99	13.16	9.88	9.82	13.39	10.14

Appendix 2 Modifying position estimation method

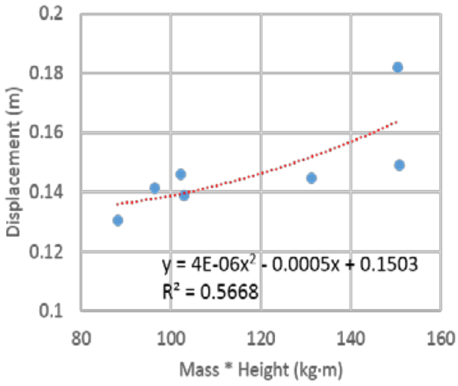
Appendix 2.1 Length between hip joint position to backseat

Figure 23 was trend line to modifying position estimation between hip joint and backseat at discussion 5.2.

Shank angle error was larger than proposed estimation method in RMSE. Correlation with GS was higher than proposed estimation method.



(a) Mass*Height, Linear expression



(b) Mass*Height, Quadratic expression

Figure 23. Trend line in linear expression (a) and quadratic expression (b).

Table 28. Shank angle error generated by different methods (Sym. : symmetric, Asym. : Asymmetric)

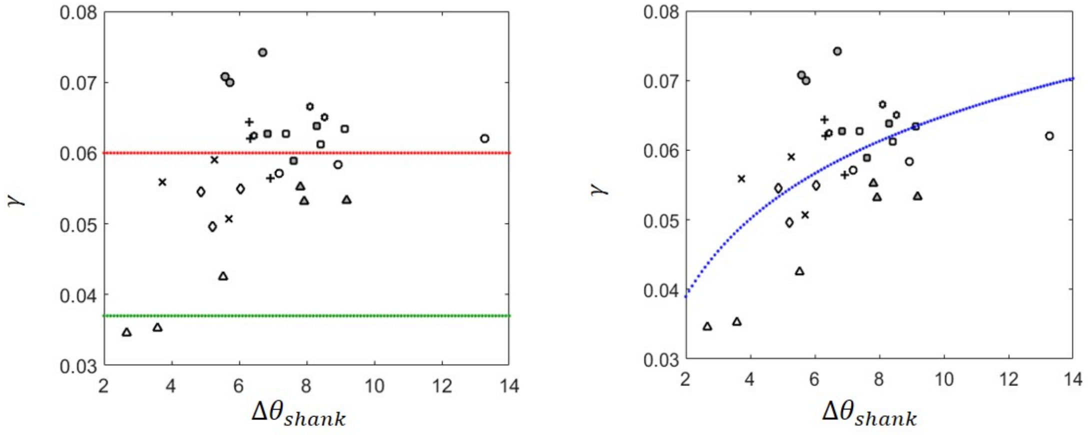
	Proposed method		**Linear expression**		**Quadratic expression**	
	Sym.	**Asym.**	**Sym.**	**Asym.**	**Sym.**	**Asym.**
RMSE (deg.)	1.28	1.92	1.15	2.49	1.15	2.07
R^2	0.38	0.38	0.59	0.40	0.61	0.44

Appendix 2.2 γ

Figure 24. was two modified estimation method to improve γ. Equation of method 2 was at equation 22.

$$\gamma = 0.0161 \ln(\Delta\theta_{shank}) + 0.0278 \quad (22)$$

Method 1 had less error and higher correlation coefficient than method 2 (Table 28). Method 1 was better to estimate thigh angle than method 2.



(a) Method 1 (b) Method 2

Figure 24. Two method to estimate γ

Table 29. RMSE and R^2 of method 1 and 2

Method	**1**	**2**
RMSE (deg.)	2.21	3.11
R^2	0.58	0.31

Appendix 2.3 Joint moment

Segment angle to calculate joint moment to compare with conventional proposed method was two trend line with mass*height and γ by method 1. RMSE of knee joint moment during sit to stand was similar or higher values than the proposed method.

Table 30. Knee joint moment error during sit to stand at symmetric sit to stand

	Proposed method	**Linear expression**	**Quadratic expression**
RMSE (Nm/kg)	0.07 $\pm$ 0.04	0.07 $\pm$ 0.03	0.08 $\pm$ 0.03
Correlation coefficient	0.98 $\pm$ 0.01	0.98 $\pm$ 0.02	0.98 $\pm$ 0.02

Table 31. Knee joint moment error during sit to stand at asymmetric sit to stand

	Proposed method		Linear expression		Quadratic expression	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
RMSE (Nm/kg)	0.08 ± 0.03	0.09 ± 0.06	0.09 ± 0.02	0.13 ± 0.04	0.08 ± 0.03	0.11 ± 0.30
Correlation coefficient	0.95 ± 0.06	0.97 ± 0.03	0.83 ± 0.02	0.97 ± 0.02	0.90 ± 0.12	0.98 ± 0.01

Quadratic expression showed good performance than proposed method to estimated maximum joint. Number of trials over 20% of error was also decreased. Quadratic method could be replaceable proposed method.

Table 32. RMSPE of knee and hip joint moment at symmetric sit to stand

	Proposed method	**Linear expression**	**Quadratic expression**
Knee (%)	9.83	10.39	9.27
Hip (%)	11.60	10.03	9.52
Trials over 20	3	1	1

Table 33. RMSPE of knee and hip joint moment at asymmetric sit to stand

	Proposed method		Linear expression		Quadratic expression	
	LW	**MW**	**LW**	**MW**	**LW**	**MW**
Knee (%)	15.15	14.18	26.24	11.88	18.60	10.81
Hip (%)	10.40	10.72	9.92	8.35	9.92	7.48
Trials over 20	3	0	3	2	2	0

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요 약 문

앉았다 일어서는 동작의 하지 관절 모멘트를 간단하게 계산하는 방법

본 논문은 앉았다 일어서는 동작의 최대 관절 모멘트를 측정하기 위한 간단한 방법에 대하여 다룬다. 앉았다 일어서는 관절 모멘트는 일상생활에서 가장 큰 힘을 내는 동작임으로, 일상생활에서 필요한 최대 관절 모멘트를 앉았다 일어서는 동작으로 측정이 될 것이라고 기대가 된다. 이러한 관절 모멘트를 계산하기 위해서는 각 관절의 위치와 그에 작용되는 힘에 의해서 계산이 된다. 현재 가지고 있는 시스템 (모션캡쳐카메라와 포스 플레이트)을 이용하여 관절 모멘트를 계산하기에는 가격이 너무 비싸고 공간 차지가 크기 때문에 임상에서 쓰이기에는 부적절하다. 이를 해결하기 위하여, 기존연구에서는 시스템을 더 간단화하기 위한 노력이 진행중이다. 관절 모멘트를 측정하는 간단한 시스템이 만들어지게 된다면, 임상에서 환자 혹은 노인들의 앉았다 일어설 때의 관절 모멘트를 측정하여 근력 향상에 도움이 될 수 있을 것으로 예상이 된다.

핵심어 : 근력, 앉았다 일어서기, 최대 관절 모멘트