Journal of Mechanical Science and Technology 29 (4) (2015) 1657~1662
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-015-0337-1

Estimation of sitting posture by using the combination of ground reaction force†

Hyeob Choi and Sukyung Park*

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, 305-701, Korea

(Manuscript Received February 26, 2014; Revised September 30, 2014; Accepted December 12, 2014)

Abstract

To avoid back pain and related diseases, an appropriate sitting posture should be maintained. Inertial measurement units (IMUs) or marker-less motion cameras, such as Kinect©, has recently been used to achieve simpler posture measurements than optical motion capture camera systems. However, multiple IMUs can affect the natural posture of users. The space requirement to guarantee reliable camera data is also somewhat excessive (>1 m) for some personal space setups. Therefore, we propose an unobtrusive method for estimating sitting posture on the basis of ground reaction force measurement, which can be achieved without the use of markers or additional space for measurement. To eliminate additional measurement information other than the ground reaction force underneath the chair and desk, we modeled the posture as a multi-segment rigid body. Several assumptions were proposed and verified to simplify the model and data processing without deteriorating the posture information. Furthermore, to examine whether the combined GRF information provides the appropriateness of the posture, we performed sitting tests for various postures. Results showed that the combinations of GRF measurement could reasonably estimate the sitting posture by the simplified rigid body model and could reliably differentiate the inappropriate forward bent posture. The results showed that the proposed method could serve as a sensing mechanism of posture monitoring systems.

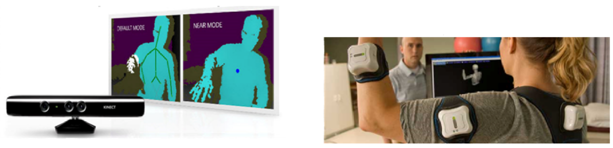
Keywords: Ground reaction force; Posture estimation; Sitting posture; Trunk angle

---

1. Introduction

For individuals who spend many hours in the sitting position, maintaining an appropriate sitting posture is important to avoid back pain and related diseases. A close correlation between bad posture and back pain has recently been reported. Murphy [1] reported that a trunk posture with an angle above 20° would increase lower back pain. Excessive forward neck stretching induced severe neck pain [2, 3] and placed additional loads on the neck muscle [4]. Therefore, portable posture measuring systems should be developed to monitor bad posture and educate users.

Compared with optical motion capture camera systems for posture measurement, inertial measurement units (IMUs) [5, 6] or marker-less motion cameras, such as Kinect©, has been used to achieve a simple manner of conducting posture measurements [7, 8] (Fig. 1). An IMU system collects the linear acceleration and angular velocity of the limbs of users and estimates sitting posture by integrating the collected data. The marker-less motion capture camera system collects images of the human body and estimates the sitting posture by analyzing the captured images on the basis of a pre-loaded human motion library. However, the use of multiple IMUs can affect the natural posture of users. The space requirement to guarantee reliable camera data is also somewhat excessive (>1 m) for some personal space setups. Therefore, we propose an unobtrusive method for estimating sitting posture on the basis of ground reaction force measurement, which can be achieved without the use of markers or additional space for measurement.



(a) (b)

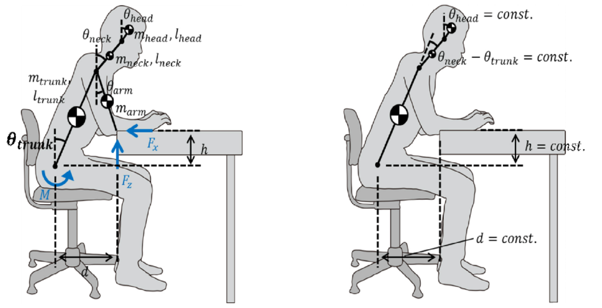
Fig. 1. Existing posture measuring system: (a) Kinect, Microsoft. Motion capture camera using RGB and depth image [9]; (b) K-health, K-vest. A motion sensing module consisting of three accelerometers, three gyros, and three magnetometers [10].

2. Methods

2.1 Model

To obtain the relationship between GRF and posture, we modeled the upper body as a four segment rigid body that consists of a head, neck, trunk, and arms with hinge joints. The arms were defined as a line segment connecting the shoulder joint to the contact point of the lower arm with the

*Corresponding author. Tel.: +82 42 350 3230, Fax.: +82 42 350 3210
E-mail address: sukyungp@kaist.ac.kr
† Recommended by Associate Editor Yoon Hyuk Kim



(a) (b)

Fig. 2. Upper-body model: (a) consisting of four segments: trunk, neck, head, and arm. The system was assumed to be a quasi-static system. Trunk angle was estimated on the basis of the assumptions and measured M, F_z, and F_x.; (b) additional conditions and restrictions. To estimate upper-body posture with minimal measurement, we assumed four more conditions. We assumed that the position of the desk, chair, and θ_{head} was constant because people gaze at monitors and do not move when working. The intersegment angle θ_1 was fixed in the model from the result of the pilot experiment.

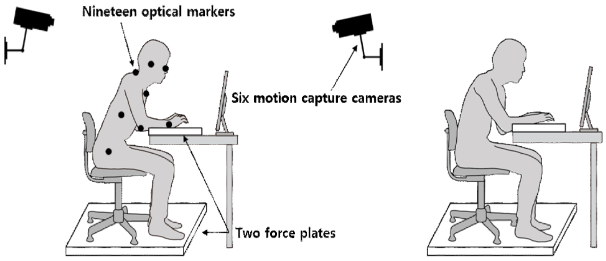
desk (Fig. 2). The head angle and intersegment angle between the neck and trunk were fixed to 10° and 22°, respectively, on the basis of the result of a pilot experiment wherein subjects watched a movie and typed the dialogues with free posture in the experimental environment during an hour. The mass and length of each segment were estimated from the anthropometric data [11] and were calibrated by using data from the straight-trunk trial. The lower body was assumed to be stationary and was not explicitly modeled. The heights of the desk and chair were set at 45 and 70 cm, respectively, and the distance between the desk and chair was set as 0 cm.

Given that the sitting posture generally does not involve rapid movement, the upper-body posture was assumed to be static. The trunk angle was then estimated from the equations of the force and moment equilibrium:

$$\begin{gathered}
\theta_{trunk} = \sin^{-1}\left(\frac{M + F_z d + F_x h - C}{\sqrt{A^2 + B^2}}\right) - \tan^{-1}\left(\frac{B}{A}\right) \\
A = \left(\frac{1}{2}m_{trunk} + m_{neck} + m_{head} + \frac{1}{2}m_{arm}\right) g l_{trunk} + \left(\frac{1}{2}m_{neck} + m_{head}\right) g l_{neck} \cos\theta_2 \ , \\
B = \left(\frac{1}{2}m_{neck} + m_{head}\right) g l_{neck} \sin\theta_2 \\
C = \frac{1}{2}m_{arm} g d + \frac{1}{2}m_{head} g l_{head} \sin\theta_1
\end{gathered} \tag{1}$$

where M, F_z, F_x, θ_1, and θ_2 are the moment on the waist, the vertical force on the desk, the horizontal force on the desk, the head angle between the neck and trunk, and the intersegment angle between the neck and trunk, respectively. The mass and length of each segment, the horizontal and vertical distance between the waist and desk, and the gravitational acceleration are denoted by m, l, d, h and g, respectively.

The moment on the waist M was calculated by the following equation:



(a) (b)

Fig. 3. Experiment setup: (a) two force plates on the desk and under the chair measured the ground reaction force and moment, and 6 motion capture cameras collected the absolute positions of 19 markers on the upper body; (b) the subjects performed the same tasks under 2 posture condition: straight posture and bent posture. Figures a and b show the straight and bent postures.

$$M = \left(M_{measured} - M_0\right) + F_z\left(x - d\right) + F_x\left(L - h\right), \tag{2}$$

where $M_{measured}$ and M_0 are the measured moment on the floor in the experiment and the moment on the floor when the subject was sitting with an upright posture, respectively. The horizontal and vertical distance between the center of the force plate on the floor and the edge of the desk are denoted by x and L, respectively.

2.2 Experiment

2.2.1 Subject and protocols

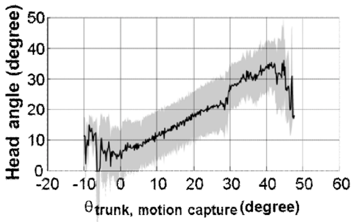
Ten healthy male subjects with no history of postural disorder participated in the sitting posture trials. The average age, weight, and height were 23.3 ± 1.7 yrs, 75.0 ± 7.8 kg, and 176.6 ± 4.2 cm, respectively. All participants read the consent approved by KAIST IRB and signed it prior to the experiment.

Three sets of sitting experiments were used for different trunk conditions: straight-, natural-, and bent-trunk postures. In the bent-trunk condition, subjects were instructed to bend their trunk as much as they can when leaning forward. Each set consisted of nine trials of leaning forward and recovery to upright sitting over 10 s. To avoid unnatural rapid motion, subjects were told to move slowly and were informed by auditory cues to lean or recover to upright sitting every 5 s. Subjects were told to look at the monitor and put their hands on top of the keyboard (Fig. 3).

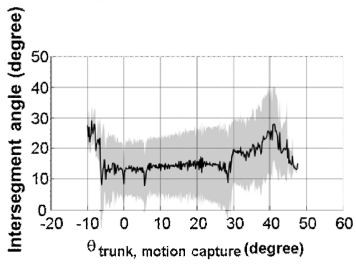
2.2.2 Measurement and data analysis

A motion capture camera system and force plates were used to measure upper the body motion of the subject and the GRF due to movement. Six cameras were set up to observe the movements of the upper body in the sagittal plane, which was averaged over the left and right sides of the body. Eleven markers were placed at the nose, tragus, C7 vertebra, center of clavicle, shoulders, sides, and pelvises [12]. Two force plates were placed under the chair and on top of the desk.

Marker data and GRF data were collected at a sampling frequency of 30 Hz, and the data were filtered by Butterworth's



(a)



(b)

Fig. 4. Head angle and intersegment angle between the neck and trunk in the straight trial. The head angle increased from 10° to 35° as the trunk angle increased from 0° to 45°. The intersegment angle was fixed at 16°. Both angles had a variance regardless of trunk angle.

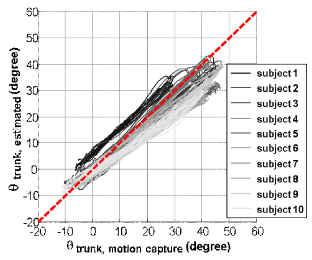
fifth-order filter with a cut-off frequency of 1 Hz to fully reserve the data repeated over 10 s. Body segment parameters were calibrated with GRF data of 0°, 10°, and 20° for the trunk angle of each subject. Error was defined as the difference between the trunk angles estimated from the GRF and marker data. To quantify the accuracy and linearity of the trunk angle estimation, goodness of fit were calculated for every 10° intervals and the whole range. To quantify the significance of the difference between the straight and bent postures, student's t-test was performed for the magnitude of the GRFs corresponding to the estimated trunk angle of 5°, 10°, 15°, and 20°, respectively.

3. Results

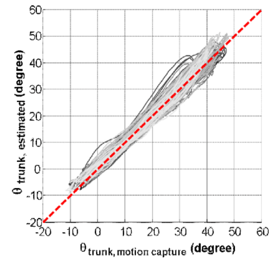
Unlike the assumption, the head angle was changed as much as half of the change in the trunk angle (Fig. 4). Variances of 8° and 10° were also observed for the head angle and intersegment angle between the neck and trunk; thus, the error caused by the differences from the assumptions should be considered. For the trunk angle estimation, the importance of body segment parameter calibration was confirmed by the R^2 value in each case (Fig. 5). After the segment parameter calibration, the trunk angle under straight posture was reasonably estimated as $R^2 > 0.9$. The R^2 values of the natural and bent posture experiments were lower than the result of the straight posture experiment. This result implied the importance of body segment calibration. Linearity was low because of a significant decrease in R^2 in the range >30° trunk angle. Corresponding to the trunk angle from the marker, a significant GRF difference between straight and bent trial was observed as a magnitude difference at all test points for eight subjects

Table 1. Significance of the difference between the GRFs of two postures.

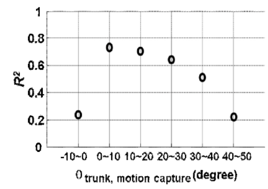
P value	5°	10°	15°	20°
Detectable subjects (n = 6)	< 0.001			
Non-detectable subjects (n = 4)	0.19±0.25	0.16±0.28	0.13±0.01	0.14±0.15



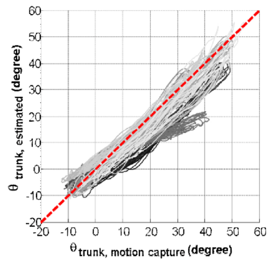
(a)



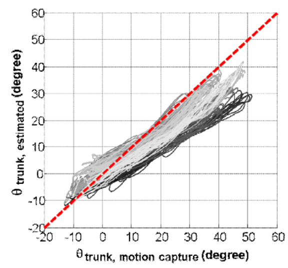
(b)



(c)



(d)



(e)

Fig. 5. (a), (b), (d) and (e) show the measured and estimated trunk angles in each conditions. (a) is the result based on anthropometric data in the straight trial, and (b), (d) and (e) are the results based on the calibrated body segment parameter in straight, natural, and bent postures. The goodness of fit for the four cases are R^2 = 0.7938, 0.9793, 0.7875, and 0.5599, respectively. (c) shows R^2 for every 10° in the straight trial and when the body segment parameters were calibrated. Except for leaning backward, the accuracy of the trunk angle estimation decreased with increasing trunk angle.

with $p < 0.001$ (Figs. 6 and 7; Table 1). Although the GRF difference decreased when the trunk angle was estimated from GRF, the postures could be distinguished by measuring the GRF for six subjects.all test points for eight subjects with $p < 0.001$ (Figs. 6 and 7; Table 1). Although the GRF difference decreased when the trunk angle was estimated from GRF, the postures could be distinguished by measuring the GRF for six subjects.

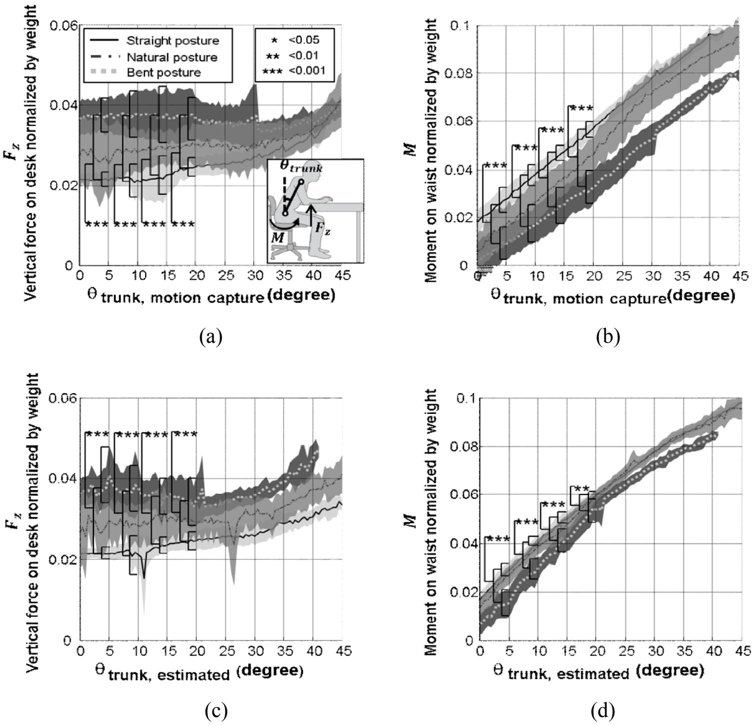


Fig. 6. Ground reaction force and moment of two postures of Subject 10: (a) and (b) Given the different shapes of trunks that have over 70% upper-body mass and length, GRF changed if the postures were different and was verified by $p < 0.05$ for four points of the trunk angle; (c) and (d) These differences were detectable by not only θ_{trunk} from the motion capture but also the estimated θ_{trunk} from the GRF data. Although, the difference of GRF decreased when it was observed on the basis of the estimated trunk angle, the difference between the two postures was still observable for the six subjects.

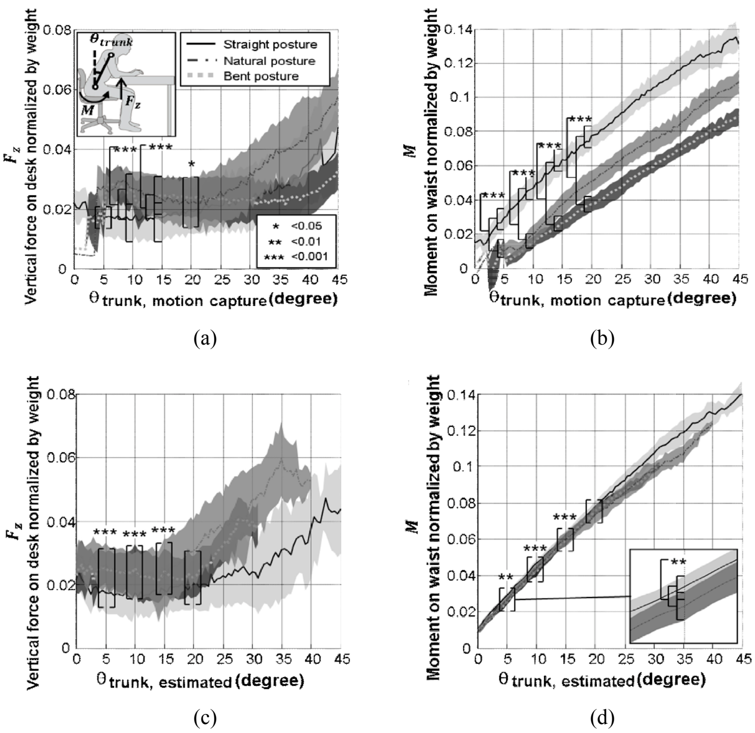
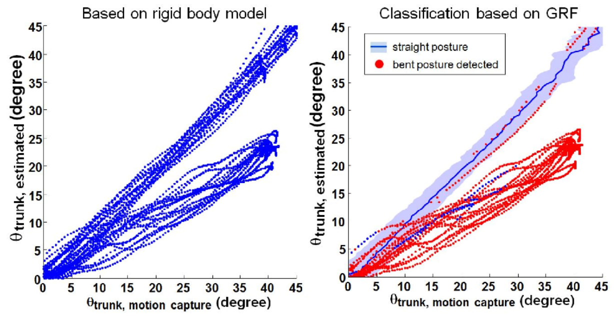


Fig. 7. Ground reaction force and moment of two postures of Subject 2; an insignificant difference was observed between postures: (a) and (b) On the basis of the θ_{trunk} from the motion capture, the GRF differences were observed at all test points for eight subjects; (c) and (d) However, two cases showed that the differences at several test points were unobservable. For this subject, the difference tested at a trunk angle of 20° was changed to be unobservable. Differences at trunk angles of 5° and 20° were changed for another subject.



(a) (b)

Fig. 8. (a) Trunk angle estimation under straight and bent posture condition on the basis of statics analysis only. Under the bent posture condition, small trunk angles were estimated because of trunk shape difference. The error from the different trunk shapes could not be detected by using simple statics analysis; (b) bent posture detection based on the GRF ratio difference. The bent posture could be detected, and the trunk angle could be estimated under a straight posture condition.

4. Discussion

The result of this research may seem obvious but is not. The result shows a natural relation wherein the reaction force on the desk and the moment on the waist increase as the trunk leans forward. However, this relation is not a simple linear relation. A critical error can also occur in trunk angle estimation by using a simple two-segment rigid body model because the human upper body consists of multiple-segments that vary in length and shape. Fig. 8(a) shows the measured and estimated trunk angle under both straight and bent posture conditions. The figure also shows the error clearly. When the trunk was bent, the estimated trunk angle was smaller than the true angle because of the small trunk length and different center of mass. This error could not be detected on the basis of static analysis. Thus, the trunk angle could not be estimated with the ground reaction force on the basis of the existing method. However, in this study, we found that the ratio of the reaction force on the desk and floor changes when the shape of the upper-body changes. We also found that the error could be detected by using this fact. This research shows that the trunk angle and upper-body posture could be estimated on the basis of the ground reaction force (Fig. 8(b)).

To minimize the required kinematic measurements, we examined whether the head angle and intersegment angle between the neck and trunk could be fixed. The result showed that errors can occur in the head angle and intersegment angle from −10° to +30° and from −10° to +10°, respectively. This result implied that the assumption for the head angle was false. By calculating the effect of the errors to the trunk angle estimation, an error of only < 2°, which is 5% of the measurement range, can occur. Considering also the result of the trunk angle estimation, a goodness of fit $R^2 > 0.9$ implied that the assumptions of the model could be allowed. The result of the trunk angle estimation also showed whether significant differences existed between the estimated trunk angles on the basis of the correctly calibrated body segment parameters. This result implied that a significant difference existed between the anthropometric data and true body segment parameter of each subject. We confirmed that the trunk angle can be estimated reasonably by using calibrated body segment parameters.

We tried to distinguish whether the load was on the neck by observing the trunk posture. The reason that makes this indirect approach possible was that the magnitude of the load on the neck is directly connected to the length of the moment arm of gravity. The length is determined by how much an individual flexes his or her neck and how much he or she leans forward the upper trunk. We confirmed that people do not move their neck largely while they were participating in the pilot experiment. Thus, we assumed that leaning the upper trunk forward significantly affected the load on the neck.

The major reason for the distinct GRF difference when the true value of the trunk angle was measured was the location of the center of mass in each posture. Whether a difference existed between the measured trunk angle and the position of the center of mass determined the total external force. This result led to a significant difference in GRF between the two postures and an error between the estimated and measured trunk angles. However, the difference caused by the above reason could be detected only while measuring the true value of the trunk angle. Given that this system inferred that a small total external force was caused by a small trunk angle and not a bent trunk, the GRF difference due to the difference between the trunk angle and position of center of mass was unobservable by this system. Thus, the only GRF difference that could be observed in this system was the ratio difference of each force of the total external force. This GRF difference could be considered a difference of dependence on the arm or waist to support the upper body. Thus, depending on the trunk posture, the subject either supported the upper trunk by using his/her arm or waist, thus causing the differences in GRF and making posture detection possible by using GRF only.

The only difference between Figs. 6 and 7 was the existence of the ground reaction force difference between two postures. The trends were also the same. On the basis of the estimated trunk angle, two graphs showed that the vertical force on the desk increased rapidly under the bent posture condition. The differences in the two graphs could be attributed to the result of the natural posture and the result based on the measured trunk angle. The result of the natural posture condition was variable for each subject and did not affect the GRF difference between straight and bent postures. On the basis of the measured trunk angle, the vertical force on the desk was small under the bent posture condition (Fig. 7(a)). Furthermore, the total external force decreased under bent posture. A comparison of the two cases under the same total external force showed that the vertical force on the desk was large under bent posture; thus, the trends of the two graphs were the same.

5. Conclusion

This research proposed a method that overcomes the shortcomings of existing posture measuring systems that require large measuring spaces and wearable sensor systems. The proposed system could estimate the trunk angle by using only the GRF measurement acquired at the desk and chair and distinguish trunk postures by using the slope and offset of GRF. We envision that this system will be used to estimate the load applied on the neck and waist for spinal injury prevention. This system can only estimate trunk angle and posture, and at this point, only a rough estimation of the neck and head can be made. The weaknesses of the proposed method can be overcome by using additional measurements. By doing so, the propose method can be used to measure the load applied on the body directly and intuitively compared with existing posture measuring systems.

Acknowledgment

This work was supported by the Ministry of Knowledge Economy, Republic of Korea, under the IT R&D program supervised by the Korea Evaluation Institute of Industrial Technology (10041059).

Nomenclature

M	: Moment on the waist
F_z	: Vertical reaction force on the desk
F_x	: Horizontal reaction force on the desk
θ_1	: Head angle
θ_2	: Intersegment angle between neck and trunk
m	: Mass of the body segment
l	: Length of the body segment
h	: Head angle
d	: Intersegment angle between neck and trunk
g	: Acceleration of gravity (9.8 m/s^2)
$M_{measured}$	: Measured moment under the chair during the experiment
M_0	: Measured moment of upright posture before the ex periment (Initial value)
L	: Vertical displacement between the force plate and the desk
x	: Horizontal displacement between the center of force plate under the chair and the desk

References

[1] S. Murphy, P. Buckle and D. Stubbs, Classroom posture and self-reported back and neck pain in schoolchildren, *Applied ergonomics*, 35 (2) (2004) 113-120.

[2] J. McAviney, D. Schulz, R. Bock, D. E. Harrison and B. Holland, Determining the relationship between cervical lordosis and neck complaints, *Journal of Manipulative and Physiological Therapeutics*, 28 (3) (2005) 187-193.

[3] C. H. Yip, T. T. Chiu and A. T. Poon, The relationship between head posture and severity and disability of patients with neck pain, *Manual therapy*, 13 (2) (2008) 148-154.

[4] S. J. Edmondston, M. Sharp, A. Symes, N. Alhabib and G. T. Allison, Changes in mechanical load and extensor muscle activity in the cervico-thoracic spine induced by sitting posture modification, *Ergonomics*, 54 (2) (2011) 179-186.

[5] Z. Ding, Z. Luo, A. Causo, I. Chen, K. Yue, S. Yeo and K. Ling, Inertia sensor-based guidance system for upperlimb posture correction, *Medical Engineering & Physics*, 35 (2) (2013) 269-276.

[6] A. Gopalai and S. A. Senanayake, A wearable real-time intelligent posture corrective system using vibrotactile feedback, *Mechatronics, IEEE/ASME Transactions on*, 16 (5) (2011) 827-834.

[7] K. Biswas and S. K. Basu, Gesture recognition using Microsoft Kinect®, *Automation, Robotics and Applications (ICARA), 2011 5th International Conference on* (2011) 100-103.

[8] L. Xia, C.-C. Chen and J. Aggarwal, Human detection using depth information by kinect, *Computer Vision and Pattern Recognition Workshops (CVPRW), 2011 IEEE Computer Society Conference on* (2011) 15-22.

[9] *http://research.microsoft.com/en-US/events/sigcse2013/technoloogies.aspx.*

[10] *http://www.k-vest.com/.*

[11] R. Drillis, R. Contini and M. Bluestein, Body segment parameters; a survey of measurement techniques, *Artificial Limbs*, 25 (1964) 44-66.

[12] L. Straker, R. Burgess-Limerick, C. Pollock, K. Murray, K. Netto, J. Coleman and R. Skoss, The impact of computer display height and desk design on 3D posture during information technology work by young adults, *J. Electromyogr. Kines.*, 18 (2) (2008) 336-349.

Hyeob Choi received his B.S. and M.S. degrees in the Department of Mechanical Engineering from KAIST, Republic of Korea, in 2012 and 2014, respectively. He is currently a Ph.D. student in the Department of Mechanical Engineering, KAIST, Republic of Korea. His research interests are sports biomechanics and modeling.

Sukyung Park is a professor in the Department of Mechanical Engineering, KAIST, Republic of Korea. She received her B.S. degree in 1995 and M.S. degree in 1997 from KAIST, Republic of Korea. She received her Ph.D. in 2002 from the University of Michigan, USA. Her research interests include biomechanics, human posture, gait control, and biomimetics.