Quantitative Evaluation Related to Disease Progression in Knee Osteoarthritis Patients During Gait

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Abstract Knee osteoarthritis (KOA) is a common joint disease of the lower limbs. Its progression reduces the patients’ quality of life. Varus thrust (VT), one of the abnormal gait patterns of KOA patients, is considered as an effective index for assessing KOA. Hence, several studies have assessed VT using various measurement methods. Since VT is the momentary lateral knee motion that increases knee varus angle and moment, optical motion capture system is widely used. However, optical motion capture system has some disadvantages in clinical usage, such as high cost, requirement of technical skills, and time-consuming attachment process. Recently, inertial measurement units (IMU) have emerged as a measurement system instead of optical motion capture systems. IMU-based method is regarded as more suitable than optical motion capture systems for VT assessment because of its simplicity. This study aimed to assess the gait of KOA patients using IMUs and to quantitatively evaluate VT based on disease progression. For this purpose, we recruited 7 healthy participants and 15 KOA patients. Subsequently, their knees were classified into 3 progression groups: 14 healthy (grade 0) knees, 9 grade 3 knees, and 14 grade 4 knees. As a gait test, all the participants wore IMUs positioned at the trunk, both thighs, and both shanks, and traversed a 10-m walkway. VT was considered as the first peak value of the mediolateral acceleration and the varus–valgus angular velocity data, which were collected via the IMUs at both shanks. Thereafter, these acquired data were compared and evaluated among the three progression groups. The results indicate that both peak values were significantly greater in the KOA patients than in the healthy subjects. Moreover, there was a significant positive correlation between the two peak values. Thus, this study is expected to contribute toward early detection of KOA.

Keywords: IMU, knee osteoarthritis, biomechanics.

1. Introduction

Knee osteoarthritis (KOA) is the most common joint disease of the lower limbs [1]. Currently, the aging population has led to an increase in KOA risk. The number of KOA patients has been increasing in the last 28 years. In 2017, there were approximately 260 million KOA patients worldwide [2]. The progression of KOA reduces the range of motion, decreases walking speed, and induces abnormal gait patterns, which deteriorates the quality of life of KOA patients [3–5]. Therefore, early detection of KOA is essential.

Varus thrust (VT), an abnormal gait characteristic of KOA patients, is the momentary lateral motion of the knee joint during the initial stage of a single stance phase [6, 7]. VT is considered as an effective dynamic evaluation index for the progression of KOA [8]. Computed tomography and X-ray imaging can be employed to evaluate KOA progression, but these techniques involve exposure to radiation and also necessitate skilled medical personnel. Hence, it is necessary to develop an alternative method that is capable of evaluating VT in a safer and more efficient manner.
To investigate the gait of KOA patients, optical motion capture systems or sensor-based analysis systems have been adopted in previous studies. Several studies employing optical motion capture systems have reported an increase in the instability of knee joints as well as a decline in the muscle force of the lower limb [9, 10]. Sharma et al. [9] reported a correlation between the increase in varus knee joint moments and disease progression. Based on the VT, Chang et al. [11] reported a significant increase in the knee varus angle and angular velocity in OA patients compared to healthy individuals. However, optical motion capture systems are associated with a few disadvantages in clinical usage, such as high cost, the requirement of technical skills, and a time-consuming attachment process.

Recently, inertial measurement units (IMU) have emerged as an alternative to the conventional optical motion capture systems [12, 13]. The IMU-based method offers advantages such as low cost, simple measurement system, and time-saving attachment process. Therefore, this method is more suitable for assessing a large number of KOA patients. In a previous study employing the sensor-based method, Kito et al. [14] defined VT as the peak mediolateral acceleration at the shank and reported a significant increase in the velocity peak calculated by integrating the acceleration observed in OA patients compared to healthy individuals.

In several previous studies using optical motion capture systems, the varus knee joint moment and angle were measured [15, 16]. However, when using the IMU-based method, incorrect values of these parameters were obtained because of the lack of force data and the drift errors. Therefore, instead of these parameters, measuring the mediolateral acceleration and the varus angular velocity is more effective for the IMU-based method. Thus, this study aimed to quantitatively evaluate VT associated with disease progression by measuring the mediolateral acceleration and varus angular velocity at the shank during the stance phase.

2. Methods

2.1 Participants

We recruited 7 healthy participants and 15 KOA patients for this study. Table 1 lists the data regarding the physical parameters of these participants. The healthy participants were students at Akita University, who did not have any walking disorder. The KOA patients were recruited at Akita University Hospital, who had not undergone knee arthroplasty in any of their legs. The disease progression of these patients was classified according to the Kellgren–Lawrence (KL) grade [17].

This study was conducted in accordance with the Declaration of Helsinki, and was reviewed and approved by the ethical committee of Akita University (Approved No. 1775).

2.2 Devices

Five IMUs (IMU-Z2, ZMP Inc., Tokyo, Japan) with a three-axis accelerometer, gyroscope, and magnetometer were used for gait measurements, at a sampling rate of 100 Hz. These IMUs were attached using a flexible band to the participant’s trunk, the frontal planes of their thighs, and the shanks of both legs.

The coordinate systems of the IMUs were aligned to the coordinate systems of the body segments while standing upright. The x-axes of the IMUs were aligned to the superoinferior axes of the body segments, pointing superiorly. The z-axes of the IMUs were aligned to the anteroposterior axes of the body segments, pointing anteriorly. In this case, the y-axes of the IMUs were aligned to the mediolateral axes of the body segments, pointing laterally at the right leg and pointing medially at the left leg. Figure 1 shows the locations at which the IMUs were attached. The data from these IMUs were transmitted to a laptop (ThinkPad X270, Lenovo Corp., Beijing, China) via Bluetooth.

2.3 Gait test

Each participant wearing the IMUs participated in a

| Table 1 | Physical parameters of participants. |
|---------|--------------------------------------|
|         | Healthy (n = 7) | KOA (n = 15) |
|         | Mean (SD)      | Mean (SD)    |
| Age [years] | 22.9 (2.63) | 68.4 (6.43) |
| Height [cm]  | 172 (5.50) | 158 (7.80) |
| Body Weight [kg] | 69.6 (9.74) | 60.7 (9.16) |
| BMI [kg/m²]   | 23.4 (2.10) | 24.3 (2.35) |

Fig. 1 IMU attachment positions. During the gait test, all IMUs were wrapped under flexible bands.
10-m free gait test thrice. To obtain stabilized gait, we set the acceleration and deceleration sections at least three steps ahead and behind, respectively, the 10-m walk.

During the gait test, the participant first stood upright and remained stationary for 5 s before commencing walking, in order to estimate the initial posture at the IMUs. After reaching the end of the deceleration section, the participant remained upright and stationary for 5 s.

The examiner walked with each KOA patient to prevent falls and also instruct when the participant should start or stop walking. In addition, the examiner counted the number of steps of the participant and recorded the time required to complete the 10-m walk. Using these measurements, the walking speed of the participant was derived. If a participant experienced discomfort during walking, the test was aborted.

2.4 Data processing
We measured the motion of a total of 44 knees. Based on the inclusion/exclusion criteria, 37 knees were included for data analyses. Subsequently, for evaluations based on KOA progression, the knees of the participants were classified into 3 progression groups: 14 knees were classified as grade 0, 9 knees as grade 3, and 14 knees grade 4 (Fig. 2).

Previous studies have reported that VT can be observed during the early stage of a stance phase and that shank motion is a significant factor. Therefore, we extracted the stance phases of each leg from the time series data using the following processes.

An extended Kalman filter-based algorithm [18] was used to estimate the attitude of the IMUs attached to both legs, and based on the shank IMU attitude relative to the thigh IMU attitude, the knee flexion angle was calculated for each leg. The heel strike (HS) timing was determined using the anteroposterior acceleration data collected via the trunk IMU, which was smoothed with a fifth-order low-pass Butterworth filter (cutoff frequency = 2 Hz) [19]. This technique reported by Zijlstra et al. [19] provides the positive to negative transition timing in the anteroposterior acceleration signal, which appears when the heel makes contact with the floor. We preliminarily confirmed that the largest error between this technique and the video-based foot impact detection was 0.03 second, which was acceptable for our study.

Based on the consecutive HS timing information for each leg, we extracted the acceleration data of the stance phase, which was the first 60% of one gait cycle.

In this study, we focused on the mediolateral acceleration data and the varus–valgus angular velocity data collected by the IMUs located at both shanks during the stance phase. Subsequently, the average values of these data were obtained for all the stance phases during the trials. In particular, the values of the acceleration and angular velocity data of the left shank were positively and negatively inverted because of the attachment direction of the IMUs. Moreover, the first peak values of the mediolateral acceleration and the varus–valgus angular velocity were considered as the characteristics of VT, and were defined as the first peak lateral acceleration (FPLA) and first peak varus angular velocity (FPVAV). To eliminate the effect of velocity, the FPLA and FPVAV values were divided by the walking speed of each participant.

For FPLA and FPVAV, one-way analysis of variance (ANOVA) with post-hoc Tukey-Kramer test were employed to compare the difference among the progression groups. Spearman’s rank-order correlation was used to evaluate the correlation between FPLA and FPVAV. The significance level was set at $p < 0.05$.

MATLAB R2016b (Mathworks Inc., Massachusetts, USA) was used for the attitude estimations, while EZR Ver. 1.37 (Jichi Medical University, Japan) was used for the statistical analyses [21].

3. Results
Figure 3 presents the representative mediolateral acceleration and varus–valgus angular velocity data of a participant measured at the shank during the stance phase. The orange arrows indicate the FPLA and FPVAV values. When there was no peak, as in the case of acceleration in Fig. 3(a), we extracted the highest value between 0% and 20% of the gait cycle, which is considered the early part of the stance phase. Then, the extracted values were determined as the FPLA and FPVAV. In each graph, the horizontal axis is the gait cycle, and the vertical axis is the mediolateral acceleration or angular velocity. Moreover, the lateral and varus, i.e., the lateral motion and adduction rotation of the shank segment, are in positive direction. In both these graphs, the orange arrow indicates the FPLA or FPVAV. As indicated by the results of grade 4, both the acceleration and the angular
velocity featured larger peak values compared with the results of grade 0.

Figure 4 presents the bar plots of FPLA and FPVAV for each progression group. The FPLA and FPVAV values for both grade 3 and grade 4 increased significantly than that for grade 0. However, there was no significant difference between the values for grades 3 and 4.

Figure 5 illustrates the correlation between FPLA and FPVAV. In the graph, the FPLA and FPVAV values of each knee are plotted as dots. A significant correlation was observed between the FPLA and FPVAV values.

4. Discussion

The acceleration trajectories along the horizontal plane and the varus–valgus angular velocity exhibited evident differences between the results of grade 0 and those of grade 4. The results indicate that as the grade increases, the acceleration trajectory extends further toward the mediolateral direction and the peak of angular velocity also increases. These differences are characteristics of VT. Therefore, measuring the acceleration and angular velocity is concluded to be an effective approach for VT assessments by the IMU-based method.

The FPLA and FPVAV values of acceleration and angular velocity in the grade 3 and grade 4 groups increased significantly when compared with the grade 0 group ($p < 0.05$). Previously, Kito et al. [14] assessed the mediolateral velocity of the shank, while Chang et al. [11] assessed the varus angle and angular velocity of knee joints. Both studies reported a significant increase in OA patients compared with healthy individuals. These results are similar to the results of this study. Therefore,
the validity of our results was verified. However, there was no significant difference between the grade 3 and grade 4 groups. As shown in Figure 4, standard deviation values were larger for grade 3 (5.64 m/s$^2$ and 23.2 deg/s) and grade 4 (3.30 m/s$^2$ and 38.9 deg/s) than for grade 0 (1.07 m/s$^2$ and 10.7 deg/s). These results are attributed to the characteristics of knees with a higher grade of progression, such as increased joint instability and decreased muscle strength. Moreover, differences in body weight and center of gravity of each participant also cause unstable motion. These factors would lead to discrepancies in the results of grade 3 and grade 4.

Figure 5 illustrates the correlation between FPLA and FPVAV, which was evaluated using Spearman rank-order correlation at a significance level of 5%. In the graph, the FPLA and FPVAV values of each knee are plotted as a dot. A significant correlation was observed between FPLA and FPVAV values.

The correlation between FPLA and FPVAV was found to be statistically significant ($p < 0.05$), and the two parameters correlated positively ($r = 0.491$). This result shows that it is effective for the KOA assessment to investigate both the acceleration and angular velocity at the shank, by employing the IMU-based measurement method. The results thus obtained indicated a significant increase in these values in the OA patients compared with the healthy group. In addition, a significant correlation between the two parameters was detected. For future studies, a larger group of participants including those with low grade KOA progression is needed to improve the reliability of the results.

5. Conclusion

This study investigated VT, a gait characteristics of KOA patients, in order to assess the first peak values of mediolateral acceleration and varus angular velocity at the shank, by employing the IMU-based measurement method. The results thus obtained indicated a significant increase in these values in the OA patients compared with the healthy group. In addition, a significant correlation between the two parameters was detected. For future studies, a larger group of participants including those with low grade KOA progression is needed to improve the reliability of the results.

Conflict of Interest

The authors have no conflicts of interest associated with this manuscript.

References

1. GBD 2017 Disease and Injury Incidence and Prevalence Collaborators: Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. Lancet. 392(10159), 1789–1858, 2018.

2. Vos T, Flaxman AD, Naghavi M, Lazano R, Michaud C, Ezzati M, et al.: Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet. 380(9859), 2163–2196, 2012.
3. Astephen JL, Deluzio KJ: Changes in frontal plane dynamics and the loading response phase of the gait cycle are characteristic of severe knee osteoarthritis application of a multidimensional analysis technique. Clin Biomech. 20(2), 209–217, 2005.

4. Balianas AJ, Hurwitz DE, Ryals AB, Karrar A, Case JP, Block JA, Andriacchi TP: Increased knee joint loads during walking are present in subjects with knee osteoarthritis. Osteoarthr Cartil. 10(7), 573–579, 2002.

5. Felson DT, Naimark A, Anderson J, Kazis L, Castelli W, Meenan RF: The prevalence of knee osteoarthritis in the elderly. The Framingham Osteoarthritis Study. Arthritis Rheum. 30, 914–918, 1987.

6. Fukaya T, Mutsuzaki H, Wadano Y: Kinematic analysis of knee varus and rotation movements at the initial stance phase with severe osteoarthritis of the knee. Knee. 22(3), 213–216, 2015.

7. Wink AE, Gross KD, Brown CA, Guermazi A, Roemer F, Niu J, Kuroyanagi Y, Nagura T, Kiriyama Y, Matsumoto H, Otani T, Wink AE, Gross KD, Brown CA, Guermazi A, Roemer F, Niu J, Kuroyanagi Y, Nagura T, Kiriyama Y, Matsumoto H, Otani T, Sharma L, Hurwitz DE, J.-M E. Thonar A, Sum JA, Lenz ME, Kuroyanagi Y, Nagura T, Kiriyama Y, Matsumoto H, Otani T, Toyama Y, Suda Y: A quantitative assessment of varus thrust in patients with medial knee osteoarthritis. Knee. 19(2), 130–134, 2012.

8. Sharma L, Hurwitz DE, J.-M E. Thonar A, Sum JA, Lenz ME, Dunlop DD, Schnitzer TJ, Kirwan-Mellis G, Andriacchi TP: Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. Arthritis Rheum. 41(7), 1233–1240, 1998.

9. Hubley-Kozey CL, Hill NA, Rutherford DJ, Dunbar MJ, Stanish WD: Co-activation differences in lower limb muscles between asymptomatic controls and those with varying degrees of knee osteoarthritis during walking. Clin Biomech (Bristol, Avon). 24, 407–414, 2009.

10. Chang AH, Chmiel JS, Moisio KC, Almagor O, Zhang Y, Cahue S, Sharma L: Varus thrust and knee frontal plane dynamic motion in persons with knee osteoarthritis. Osteoarthr Cartil. 21(11), 1668–1673, 2013.

11. Pernoo P: 25 years of lower limb joint kinematics by using inertial and magnetic sensors: A review of methodological approaches. Gait Posture. 51, 239–246, 2017.

12. O’Reilly M, Caulfield B, Ward T, Johnston W, Doherty C: Wearable Inertial Sensor Systems for Lower Limb Exercise Detection and Evaluation: A Systematic Review. Sports Med. 48, 1221–1246, 2018.

13. Kito N, Shimazawa S, Yuge T, Okumura K, Sugawa S, Yoshimoto S, Ibara H, Miwa M, Kouya H, Okada S: Noninvasive acceleration measurements to characterize knee osteoarthritis in gait. Phys Ther Jpn. 31(1), 86–94, 2004. (in Japanese)

14. Mündermann A, Dyrbj CO, Andriacchi TP: Secondary gait changes in patients with medial compartment knee osteoarthritis: increased load at the ankle, knee, and hip during walking. Arthritis Rheum. 52(9), 2835–2844, 2005.

15. Mills K, Hettinga BA, Pohl MB, Ferber R: Between-limb kinematic asymmetry during gait in unilateral and bilateral mild to moderate knee osteoarthritis. Arch Phys Med Rehabil. 94(11), 2241–2247, 2013.

16. Kellogg JH, Lawrence JS: Radiological assessment of osteoarthritis. Ann Rheum Dis. 16(4), 494–502, 1957.
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