INTRODUCTION
Hallux valgus is characterized by valgus deformation of the first metatarsophalangeal (MTP) joint, abduction of the proximal phalanx of the great toe, internal rotation of the metatarsal, and broad feet.

Anatomical factors involved in the development of hallux valgus differ from those in healthy individuals, e.g., an increase in metatarsal angle, extension of the first metatarsal, and a rounded metatarsal head. Moreover, patients with hallux valgus showed an increased progressive foot angle, increased heel valgus angle, decreased range of ankle dorsiflexion, and decreased range of dorsiflexion of the first MTP joint in the stance phase during gait. A study that evaluated plantar pressure showed that patients with hallux valgus had increased load on the toe and a higher valgus force on the forefoot during late stance. In cases of hallux valgus, excessive pronation of the first MTP joint displaces the pelvic inclination and causes back pain. When hallux valgus
becomes severe, the knee abduction moment required to prevent loading on the hallux has been suggested to contribute to knee osteoarthritis.\textsuperscript{10} Hallux valgus has additionally been associated with adverse effects on other parts of the body.\textsuperscript{11} However, no previous study has focused on examining hallux valgus during gait to determine the characteristic factors associated with gait speed. In a previous study, patients with post-surgical metatarsal osteotomy demonstrated that gait ability remained at the pre-surgical level.\textsuperscript{12–14} However, segments other than the MTP remained malaligned, weak, and with limited ranges of motion. It is presumed that the decrease in foot function resulting from hallux valgus affects other joints and reduces gait speed. Therefore, both local and gait characteristics should be examined. This study aimed to examine the gait abilities and related factors of subjects with hallux valgus to obtain useful information for rehabilitation of hallux valgus.

**MATERIALS AND METHODS**

The participants were 10 people with hallux valgus (hallux valgus group: 2 men and 8 women, average age 74.4 ± 6.4 years, average height 157.7 ± 7.3 cm, average weight 58.7 ± 9.9 kg) and 10 people without hallux valgus (control group: 2 men and 8 women, average age 71.3 ± 5.3 years, average height 155.7 ± 6.3 cm, average weight 53.1 ± 8.8 kg). Hallux valgus was measured using a foot printer (SMTB-S: Bauerfeind, Germany), and the hallux valgus angle was defined as ≥20°.\textsuperscript{15} No participant had a history of orthopedic surgery and none had pain at rest or during gait. This study was conducted after obtaining approval from the Ethics Committee of Kansai University of Health Sciences (reference number 19-04). The foot morphology from paper transferred using a personal computer. The digitized landmarks were the top of the heads, the midpoint between the auricles, the sternum, the center of the shoulder joints [right (Rt) and left (Lt)], the center of the elbow joints (Rt and Lt), the center of the wrist joints (Rt and Lt), the metacarpophalangeal joints (Rt and Lt), the center of the hip joints (Rt and Lt), the center of the knee joints (Rt and Lt), the center of the ankle joints (Rt and Lt), the calcaneus (Rt and Lt), the MTP joints (Rt and Lt), the tip of the toes (Rt and Lt), the midpoint between the hip joints, and the iliac crest above the great trochanter (Rt and Lt). The x-axis of the global coordinate system corresponded to the long axis of locomotion, the y-axis corresponded to the mediolateral axis of locomotion, and the z-axis corresponded to the vertical direction. Errors in the three-dimensional motion analysis system were ±0.05 cm (x-axis), ±0.04 cm (y-axis), and ±0.05 cm (z-axis). Data were smoothed using a three-point moving average with low-pass filtering at 5 Hz. The step length was calculated by measuring the linear distance of the HC point of the trailing extremity to the leading point at which the vertical force component disappeared. Furthermore, the stance phase lasted from HC to TO. The first peak value of the vertical force component (P1) resulted from HC, and the second peak value of the vertical force component is termed P2. The stance phase was divided into the early phase, from HC to P1; the middle phase, from P1 to P2; and the late phase, from P2 to TO (Fig. 1A). The ground reaction force measured during gait was resolved into front–rear (X, Fig. 1B), lateral (Y, Fig. 1C), and vertical (Z) components from the early to the late stance phase. The respective impulses were calculated by integrating the reaction forces during the early, middle and late stance phases. The impulse forces were normalized using the body mass of each participant. The total length at the center of pressure (T-COP), X-COP and Y-COP, respectively, were calculated as the COP trajectory length, the component of COP in the front–rear direction, and the component of COP in the lateral direction throughout the stance phase. T-COP and X-COP were normalized using the foot length, whereas Y-COP was normalized using the foot width.

Subjects’ gaits were recorded using four high-speed cameras (Exilim EX-F1, CASIO, Japan) at a sampling rate of 180 Hz while subjects twice walked a distance of 5 m indoors on a flat surface; then a three-dimensional motion analyzer (Frame-DIAS IV: DKH, Japan) was used. The optical axes between adjacent cameras were approximately 120° apart. Three-dimensional coordinates were calculated using the direct linear transformation method. Twenty-six body landmarks were digitized using Frame-DIASIV software on a personal computer. The digitized landmarks were the top of the heads, the midpoint between the auricles, the sternum, the center of the shoulder joints [right (Rt) and left (Lt)], the center of the elbow joints (Rt and Lt), the center of the wrist joints (Rt and Lt), the metacarpophalangeal joints (Rt and Lt), the center of the hip joints (Rt and Lt), the center of the knee joints (Rt and Lt), the center of the ankle joints (Rt and Lt), the calcaneus (Rt and Lt), the MTP joints (Rt and Lt), the tip of the toes (Rt and Lt), the midpoint between the hip joints, and the iliac crest above the great trochanter (Rt and Lt). The x-axis of the global coordinate system corresponded to the long axis of locomotion, the y-axis corresponded to the mediolateral axis of locomotion, and the z-axis corresponded to the vertical direction. Errors in the three-dimensional motion analysis system were ±0.05 cm (x-axis), ±0.04 cm (y-axis), and ±0.05 cm (z-axis). Data were smoothed using a three-point moving average with low-pass filtering at 5 Hz. The step length was calculated by measuring the linear distance of the HC point of the trailing extremity to the leading
**Fig. 1** (A) Definition of gait phases based on the vertical component of the ground reaction force. The first peak of the vertical component was defined as P1 and the second as P2. The stance phase was divided into the following three phases: early, from heel contact (HC) to P1; middle, from P1 to P2; and late, from P2 to toe-off (TO). (B) The front–rear force component of the ground reaction force. (C) The lateral force component of the ground reaction force.
extremity. The distance between the heels during the double stance phase was defined as the step width. The touchdown distance (TD)\(^5\) was defined as the anterior horizontal distance between the heel of the touchdown foot and the body’s center of mass (COM) calculated using body segment inertia parameters\(^6\) at the moment of foot touchdown. The release distance (RD)\(^5\) was calculated as the anterior horizontal distance between the toe of the releasing foot and the COM at the moment of foot release (Fig. 2A). The measured length was divided by the participant’s height for normalization. Body segment inertia parameters\(^6\) were used to calculate the COM position at each point. The highest and lowest

Fig. 2  (A) Definitions of the touchdown distance (TD) and the release distance (RD) indices using the body’s center of mass (COM) during gait. TD is the distance between the heel contact point and COM at the moment of touchdown. RD is the distance between the COM and the toe of the releasing foot at the moment of foot release. (B) An index using the body’s center of mass acquired using motion analysis during gait. The participants underwent two height measurements of the COM on the vertical axis of the sagittal plane at HC and TO. The highest and lowest COM positions were measured during gait.
points were identified based on the COM displacement in the vertical direction throughout the gait cycle. The height of the COM was calculated as a percentage of the body height. The gait speed was calculated based on the anterior displacement of the COM over two steps. **Figure 2B** illustrates the typical forms that subjects adopt during gait trials at HC and TO.

The angle of the hip joint was defined as the angle between the line from the center of the thorax at the sternum level to the hip joint and the line from the knee joint to the hip joint (Fig. 3). The knee joint angle was defined as the angle between the line from the hip joint to the knee joint and the line from the ankle joint to the knee joint. The ankle joint angle was defined as the angle between the line from the knee joint to the ankle joint and the line from the MTP joint to the ankle joint. Flexed positions of the hip and knee and the dorsal flexion position of the ankle were defined as positive angles. These angles were measured on both the step and kicking sides during gait at HC, TO, and peak P2. The trunk angle in the sagittal plane was defined as the angle between the line from the hip joint to the center of the thorax at the sternum level and the vertical (Fig. 3).

Each parameter in the hallux valgus group and the control group was compared using the Mann–Whitney U-test. All analyses considered \( P < 0.05 \) as the cutoff for statistical significance. All statistical analyses were performed using the SPSS version 12.0 software (SPSS Japan, Japan).

**RESULTS**

The hallux valgus angle of the hallux valgus group was \( 27.3 \pm 6.7^\circ \) and that of the control group was \( 6.3 \pm 3.9^\circ \). The average foot length and foot width were \( 22.2 \pm 1.0 \) and \( 8.2 \pm 0.6 \) cm, respectively, in the hallux valgus group and \( 21.2 \pm 1.2 \) and \( 8.2 \pm 0.6 \) cm, respectively, in the control group. There was no difference in foot length or foot width between the two groups. The hallux valgus group had a hallux valgus angle of \( \geq 15^\circ \) on both sides. In the hallux valgus group, the ground reaction force showed a significant increase in the Y-direction for each stance phase (early stance: \( P=0.01, 95\%CI: 0.4–4.8 \text{ N·s} \), middle stance: \( P=0.03, 95\%CI: 3.4–16.3 \text{ N·s} \), late stance: \( P=0.03, 95\%CI: 2.8–6.7 \text{ N·s} \)) and in the Z-direction for the late stance phase (\( P=0.04, 95\%CI: 57.4–158.9 \text{ N·s} \)).

![Fig. 3. Definitions of the joint angles and trunk inclination during gait. These angles were measured on both the step and kicking sides at heel contact, P2 peak, and toe-off.](image)
There were no significant differences in stance time or any COP length between the two groups for any gait phase (Table 2). Three-dimensional motion analyzer measurements showed that the gait speed significantly decreased in the hallux valgus group compared to the control group (P=0.03, 95%CI: 3.5°–17.6°), at TO (P=0.03, 95%CI: 2.3°–10.6°), and at peak P2 (P=0.02, 95%CI: 4.5°–18.6°), whereas the dorsal flexion of the ankle at peak

Table 1. Area under the ground reaction force versus time curve during gait

|                      | X (N·s)  | Y (N·s)  | Z (N·s)  |
|----------------------|----------|----------|----------|
| Hallux valgus group  |          |          |          |
| (n=10)               |          |          |          |
| Early stance         | 15.1±4.7 | 0.6±2.4 *| 108.3±44.6|
| Middle stance        | 3.3±3.2  | 11.6±5.1 *| 293.2±46.2|
| Late stance          | −20.6±4.6| 2.9±1.8 *| 101.1±22.2*|
| Control group        |          |          |          |
| (n=10)               |          |          |          |
| Early stance         | 17.4±17.5| −0.8±1.9 | 105.8±46.5|
| Middle stance        | 4.6±5.3  | 5.2±4.8  | 309.0±75.5|
| Late stance          | −19.5±5.4| 0.4±2.5  | 89.7±25.2 |

The ground reaction force during gait was separated into front–rear (X), lateral (Y), and vertical (Z) components from the early to the late stance phases. The ground reaction force of each walking phase was then integrated and normalized by the body mass. The force plate measurement showed significant increases in the hallux valgus group in the Y-direction for all stance phases and in the Z-direction for the late stance phase.

*P<0.05.

Table 2. Normalized center of pressure lengths and stance time during gait

|                      | TCOP length | X-COP length | Y-COP length | Stance time (ms) |
|----------------------|-------------|--------------|--------------|------------------|
| Hallux valgus group  |             |              |              |                  |
| (n=10)               |             |              |              |                  |
| Early stance         | 4.7±1.1     | 3.9±1.1      | 5.1±1.6      | 138.5±22.6       |
| Middle stance        | 5.8±0.6     | 4.9±0.8      | 7.3±3.7      | 329.0±55.2       |
| Late stance          | 5.8±1.2     | 4.4±1.0      | 8.2±3.3      | 159.2±32.7       |
| Control group        |             |              |              |                  |
| (n=10)               |             |              |              |                  |
| Early stance         | 4.4±1.2     | 2.1±0.7      | 5.6±2.1      | 141.6±30.6       |
| Middle stance        | 5.7±1.1     | 4.4±1.0      | 7.9±2.6      | 331.4±33.9       |
| Late stance          | 6.2±1.2     | 4.5±0.9      | 9.9±3.0      | 148.8±28.3       |

COP, center of pressure. TCOP, total COP. X-COP, component of COP in the front–rear direction. Y-COP, component in the lateral direction. TCOP and X-COP lengths were divided by the foot length. Y-COP lengths were divided by the foot width.

Table 3. Walking speed and distance factors

|                      | Gait speed (m/s) | Step length (%) | Step width (%) | TD (%) | RD (%) |
|----------------------|------------------|-----------------|---------------|--------|--------|
| Hallux valgus group  | 0.9±0.1          | 36.8±7.0        | 4.4±2.2       | 16.5±4.1| 17.9±4.7|
| (n=10)               |                  |                 |               |        |        |
| Control group        | 1.2±0.1 **       | 39.9±2.6 *      | 4.3±3.2       | 19.3±1.8*| 17.8±2.8|
| (n=10)               |                  |                 |               |        |        |

TD, touchdown distance; RD, release distance.

The distances were normalized using the height of the subject. The gait speed, step length, and TD were significantly larger in the hallux valgus group than that in the control group.

*P<0.05, **P<0.01.
P2 significantly decreased ($P=0.04, 95\%CI: 3.2°–14.2°$). No significant differences were observed for the other measured parameters (Table 4).

**DISCUSSION**

This study examined the characteristics of hallux valgus and related factors during gait. The hallux valgus group had decreased gait speed, decreased step length, and shortened TD. Furthermore, the results from the force plates indicated that the load on the anterior medial side of the toe increases the valgus stress, resulting in increased lateral and vertical component forces in the late stance phase in the hallux valgus group. In fact, the lateral component force in the stance phase persisted throughout the early, middle, and late phases. Therefore, in the hallux valgus group, the medial shear force (as the lateral component of the ground reaction force) demonstrated a significant increase compared to the control group. In previous studies, patients with hallux valgus had pronation contact or flat foot during gait in all stance phases. A similar phenomenon occurred in the current study, and the ground reaction force was different between patients with hallux valgus and healthy participants. It can be inferred that the increased lateral component force from the early stance phase persisted throughout the middle and late phases. Therefore, in the hallux valgus group, the medial shear force (as the lateral component of the ground reaction force) demonstrated a significant increase compared to the control group. In previous studies, patients with hallux valgus had pronation contact or flat foot during gait in all stance phases.

The trunk inclination angles during gait were significantly larger in the hallux valgus group at HC, TO, and peak P2. The dorsal flexion of the ankle was significantly smaller in the hallux valgus group at peak P2. *$P<0.05$.

P2 significantly decreased ($P=0.04, 95\%CI: 3.2°–14.2°$). No significant differences were observed for the other measured parameters (Table 4).

**Table 4.** The angles of the lower limbs and the trunk inclination during gait

|                      | HC                  | P2 Peak             | TO                  |
|----------------------|---------------------|---------------------|---------------------|
|                      | Step side           | Kicking side        | Step side           | Kicking side        |
| Hallux valgus group  |                     |                     |                     |
|                      |                     |                     |                     |
| Hip joint angle (°)  | 36.0±8.4            | −7.3±11.4           | 37.5±7.8            | −1.7±12.8           | 25.3±11.8            | −0.7±17.8            |
| Knee joint angle (°) | 7.8±5.2             | 12.8±5.9            | 8.4±5.7             | 11.1±6.5            | 15.4±8.6             | 37.0±14.4            |
| Ankle joint angle (°)| −10.8±4.3           | 7.0±5.6             | −9.9±6.0            | 5.4±8.1 *           | −6.0±5.0             | −20.2±9.5            |
| Trunk inclination (°)| 10.8±6.7 *          | 11.1±7.6 *          | 5.9±7.6 *           |                     |
| Control group        |                     |                     |                     |
|                      |                     |                     |                     |
| Hip joint angle (°)  | 32.6±9.0            | −7.1±6.2            | 34.8±6.2            | −6.5±4.6            | 20.5±6.5             | −0.5±10.4            |
| Knee joint angle (°) | 5.6±5.0             | 12.9±7.0            | 5.5±5.1             | 9.6±5.4             | 12.2±5.7             | 40.9±12.6            |
| Ankle joint angle (°)| −14.8±6.5           | 10.0±4.8            | −13.6±6.2           | 11.2±5.8            | −10.8±6.5            | −17.8±6.1            |
| Trunk inclination (°)| 6.8±3.0             | 5.9±3.3             | 1.6±5.5             |                     |

The trunk inclination angles during gait were significantly larger in the hallux valgus group at HC, TO, and peak P2. The dorsal flexion of the ankle was significantly smaller in the hallux valgus group at peak P2. *$P<0.05$.

COM displacement during gait is frequently used as an indicator of gait efficiency or as a complement to standard gait analysis. For example, gait analysis using COM has been reported during dynamic balancing in elderly people who underwent total knee replacement or total hip arthroplasty. We evaluated the COM displacement and investigated the characteristics of hallux valgus while subjects were walking. A comparison between the hallux valgus and...
control groups showed that the former had reduced vertical movement during gait because they maintained COM at a high position. During normal gait, the COM is at its highest position in middle stance, representing increased potential energy, but this gradually decreases toward the late stance phase. This increased potential energy is converted into kinetic energy, which is responsible for the propulsive force of gait. Based on the measured COM displacements during gait, it is considered that the lower leg cannot be tilted to convert the potential energy increase in the middle stance to kinetic energy because the hallux valgus group has limited ankle dorsiflexion. A previous study that focused on the gait of participants with hallux valgus reported decreased ground reaction forces in subjects with higher hallux valgus angles. Further, subjects with hallux valgus-related pain showed a decrease in the ground reaction force. Therefore, we excluded patients with painful hallux valgus in the current study. However, gait analysis should be performed in subjects with a range of hallux valgus angles and symptoms to investigate the effects of the severity of hallux valgus on the measured results. Patients with moderate or severe hallux valgus reportedly have higher vertical instability and higher risk of falls on irregular ground than those with mild hallux valgus. Therefore, the effects of the severity of hallux valgus on subjects walking on uneven ground and climbing stairs should be elucidated.

One limitation of this study is that the number of subjects was small. Also, evaluations using a three-dimensional motion analyzer cannot determine the movement of joints such as the motion of the toes distal to the MTP joint and sagittal plane movement. In the future, gait analysis including detailed ankle joint movements could be improved by considering the limitations in ankle dorsiflexion and longitudinal arch function.

**CONCLUSIONS**

The hallux valgus group had restricted ankle dorsiflexion during the late stance phase of gait and showed an increased lateral force component during all stance phases and an increased vertical force component to the toe during the late stance phase. According to these results, the hallux valgus group was considered to have reduced gait speed because of shortened TD and a continuously high position of the COM. Therefore, the increased potential energy could not be converted to kinetic energy in subjects with hallux valgus.

**REFERENCES**

1. Nix S, Smith M, Vicenzino B: Prevalence of hallux valgus in the general population: a systematic review and meta-analysis. J Foot Ankle Res 2010;3:21. DOI:10.1186/1757-1146-3-21, PMID:20868524
2. Nguyen US, Hillstrom HJ, Li W, Dufour AB, Kiel DP, Procter-Gray E, Gagnon MM, Hannan MT: Factors associated with hallux valgus in a population-based study of older women and men: the MOBILIZE Boston Study. Osteoarthritis Cartilage 2010;18:41–46. DOI:10.1016/j.joca.2009.07.008, PMID:19747997
3. Roddy E, Zhang W, Doherty M: Prevalence and associations of hallux valgus in a primary care population. Arthritis Rheum 2008;59:857–862. DOI:10.1002/art.23709, PMID:18512715
4. Nishimura A, Fukuda A, Nakazora S, Uchida A, Sudo A, Kato K, Yamada T: Prevalence of hallux valgus and risk factors among Japanese community dwellers. J Orthop Sci 2014;19:257–262. DOI:10.1007/s00776-013-0513-z, PMID:24338050
5. Kosk K, Luukinen H, Laippala P, Kivelä SL: Physiological factors and medications as predictors of injurious falls by elderly people: a prospective population-based study. Age Ageing 1996;25:29–38. DOI:10.1093/ageing/25.1.29, PMID:8670526
6. Menz HB, Lord SR: Gait instability in older people with hallux valgus. Foot Ankle Int 2005;26:483–489. DOI:10.1177/107110070502600610, PMID:15960916
7. Nix SE, Vicenzino BT, Collins NJ, Smith MD: Characteristics of foot structure and footwear associated with hallux valgus: a systematic review. Osteoarthritis Cartilage 2012;20:1059–1074. DOI:10.1016/j.joca.2012.06.007, PMID:22771775
8. Nix SE, Vicenzino BT, Collins NJ, Smith MD: Gait parameters associated with hallux valgus: a systematic review. J Foot Ankle Res 2013;6:9. DOI:10.1186/1757-1146-6-9, PMID:23497584
9. Perera AM, Mason L, Stephens MM: The pathogenesis of hallux valgus. J Bone Joint Surg Am 2011;93:1650–1661. DOI:10.2106/JBJS.H.01630, PMID:21915581

**CONFLICTS OF INTEREST**

The authors declare that they have no conflicts of interest.
10. Shih KS, Chien HL, Lu TW, Chang CF, Kuo CC: Gait changes in individuals with bilateral hallux valgus reduce first metatarsophalangeal loading but increase knee abductor moments. Gait Posture 2014;40:38–42. DOI:10.1016/j.gaitpost.2014.02.011, PMID:24637011

11. O’Leary CB, Cahill CR, Robinson AW, Barnes MJ, Hong J: A systematic review: the effects of podiatrical deviations on nonspecific chronic low back pain. J Back Musculoskelet Rehabil 2013;26:117–123. DOI:10.3233/BMR-130367, PMID:23640312

12. Klugarova J, Janura M, Svoboda Z, Sos Z, Stergiou N, Klugar M: Hallux valgus surgery affects kinematic parameters during gait. Clin Biomech (Bristol, Avon) 2016;40:20–26. DOI:10.1016/j.clinbiomech.2016.10.004, PMID:27792950

13. Gould N, Schneider W, Ashikaga T: Epidemiological survey of foot problems in the continental United States: 1978-1979. Foot Ankle 1980;1:8–10. DOI:10.1177/107110078000100104, PMID:6115797

14. Schuh R, Hofstaetter SG, Adams SB Jr, Pichler F, Kristen KH, Trnka HJ: Rehabilitation after hallux valgus surgery: importance of physical therapy to restore weight bearing of the first ray during the stance phase. Phys Ther 2009;89:934–945. DOI:10.2522/ptj.20080375, PMID:19608631

15. Nishimori T, Ito A: Correlation of walking speed with pelvic or lower movements of healthy young males. J Phys Ther Sci 2011;23:883–887. DOI:10.1589/jpts.23.883

16. Okada H, Ae M, Fujii N, Morioka Y: Body segment inertia properties of Japanese elderly. Soc Biomech Jpn 1996;13:125–139.

17. Winter DA, Patla AE, Patla AE, Frank JS, Walt SE: Biomechanical gaiting pattern changes in the fit and healthy elderly. Phys Ther 1990;70:340-7.

18. Hahn ME, Chou LS: Age-related reduction in sagittal plane center of mass motion during obstacle crossing. J Biomech 2004;37:837–844. DOI:10.1016/j.jbiomech.2003.11.010, PMID:15111071

19. Mandeville D, Osternig LR, Chou LS: The effect of total knee replacement surgery on gait stability. Gait Posture 2008;27:103–109. DOI:10.1016/j.gaitpost.2007.02.009, PMID:17419059

20. Nankaku M, Tsuboyama T, Kakinoki R, Keiichi K, Kanzaki H, Mito Y, Nakamura T: Gait analysis of patients in early stages after total hip arthroplasty: effect of lateral trunk displacement on walking efficiency. J Orthop Sci 2007;12:550–554. DOI:10.1007/s00776-007-1178-2, PMID:18040637

21. Saunders JB, Inman VT, Eberhart HD: The major determinants in normal and pathological gait. J Bone Joint Surg Am 1953;35:543–558. DOI:10.2106/00004623-195335030-00003, PMID:13069544

22. Kim EJ, Shin HS, Takatori N, Yoo HJ, Cho YJ, Yoo WJ, Lee DY, Lee DY: Inter-segmental foot kinematics during gait in elderly females according to the severity of hallux valgus. J Orthop Res 2020;38:2409–2418. DOI:10.1002/jor.24657, PMID:32162717