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ORIGINAL ARTICLE

Examination of gait characteristics and related factors in elderly subjects with and without hallux valgus

Takaki Yoshida, PhD, PT Yoshitsugu Tanino, PhD, PT Tetsuya Nakao, PhD, PT Wataru Yamazaki, MS, PT and Toshiaki Suzuki, PhD, PT

Objective: Elderly people with hallux valgus have decreased gait speed, which can result in reduced capacity to perform the activities of daily living. Therefore, this study examined the gait ability and related factors of patients with hallux valgus. **Methods:** The study participants were 10 patients with hallux valgus and 10 without. Ground reaction forces were measured as front–rear (X), lateral (Y), and vertical (Z) components from the early to late stance phases. Three-dimensional motion analysis was used to measure gait speed; touchdown distance; release distance; the angles of the limb joints and trunk at heel contact, toe-off, and peak ground reaction force; and the center of mass (COM) displacement in the sagittal plane. The height of the COM was calculated as a percentage of the body height. The hallux valgus and control groups were compared using the Mann–Whitney U-test. **Results:** In the hallux valgus group, the ground reaction force showed a significant increase in the Y component in each stance phase and in the Z component in the late stance phase. The lowest COM position in the hallux valgus group was significantly higher than that in the control group, resulting in a smaller difference in COM height over a gait cycle. **Conclusions:** The hallux valgus group was found to have reduced gait speed because of a shortened touchdown distance. Moreover, the continued high COM position in the hallux valgus group meant that potential energy could not efficiently be converted to kinetic energy.

Key Words: gait, ground reaction force; hallux valgus; three-dimensional motion analysis

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.1) Its prevalence is reportedly 58% and 25%, respectively, in adult women and men in the United States; 28.4% for adults in the UK (valgus angle, ≥15°); and 29.8% of the population aged >65 years (hallux valgus angle ≥20°).2–4) Hallux valgus is considered a risk factor for falling in elderly people; in fact, it is the foot disorder most relevant to falls.5) Elderly people with decreased gait speed as a result of hallux valgus are suggested to have impaired activities of daily living.6)

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.7) 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.8) 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.9) In cases of hallux valgus, excessive pronation of the first MTP joint displaces the pelvic inclination and causes back pain. When hallux valgus

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Clinical Physical Therapy Laboratory, Kansai University of Health Sciences, Osaka, Japan
Correspondence: Takaki Yoshida, PhD, PT, Clinical Physical Therapy Laboratory, Kansai University of Health Sciences, 2-11-1 Wakaba, Kumatori, Sennan, Osaka 590-0482, Japan, E-mail: t.yoshida@kansai.ac.jp

becomes severe, the knee abduction moment required to prevent loading on the hallux has been suggested to contribute to knee osteoarthritis.[10] Hallux valgus has additionally been associated with adverse effects on other parts of the body.[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.[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 $\geq 20°$.[1] 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 foot printer was measured as follows: the foot length was defined as the length of the major axis from the heel to the tip of the longest toe, the foot width was defined as the widest horizontal axis of the forefoot, and the hallux valgus angle was defined as the angle the first toe made with a line drawn from the outer part of the heel to the outermost part of the toe. The ground reaction force was measured using two buried force plates (BP400600: AMTI 40 × 60 cm, Japan) and recorded at a sampling frequency of 100 Hz. Barefoot participants were requested to walk a distance of 5 m at their normal walking speed and to step on the pressure plates so as to naturally make contact with the sole of the foot without adjusting their stride length. Ground reaction force data were evaluated at heel contact (HC), i.e., the first vertical component obtained when the heel touched the force plate, and toe-off (TO), i.e., the 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

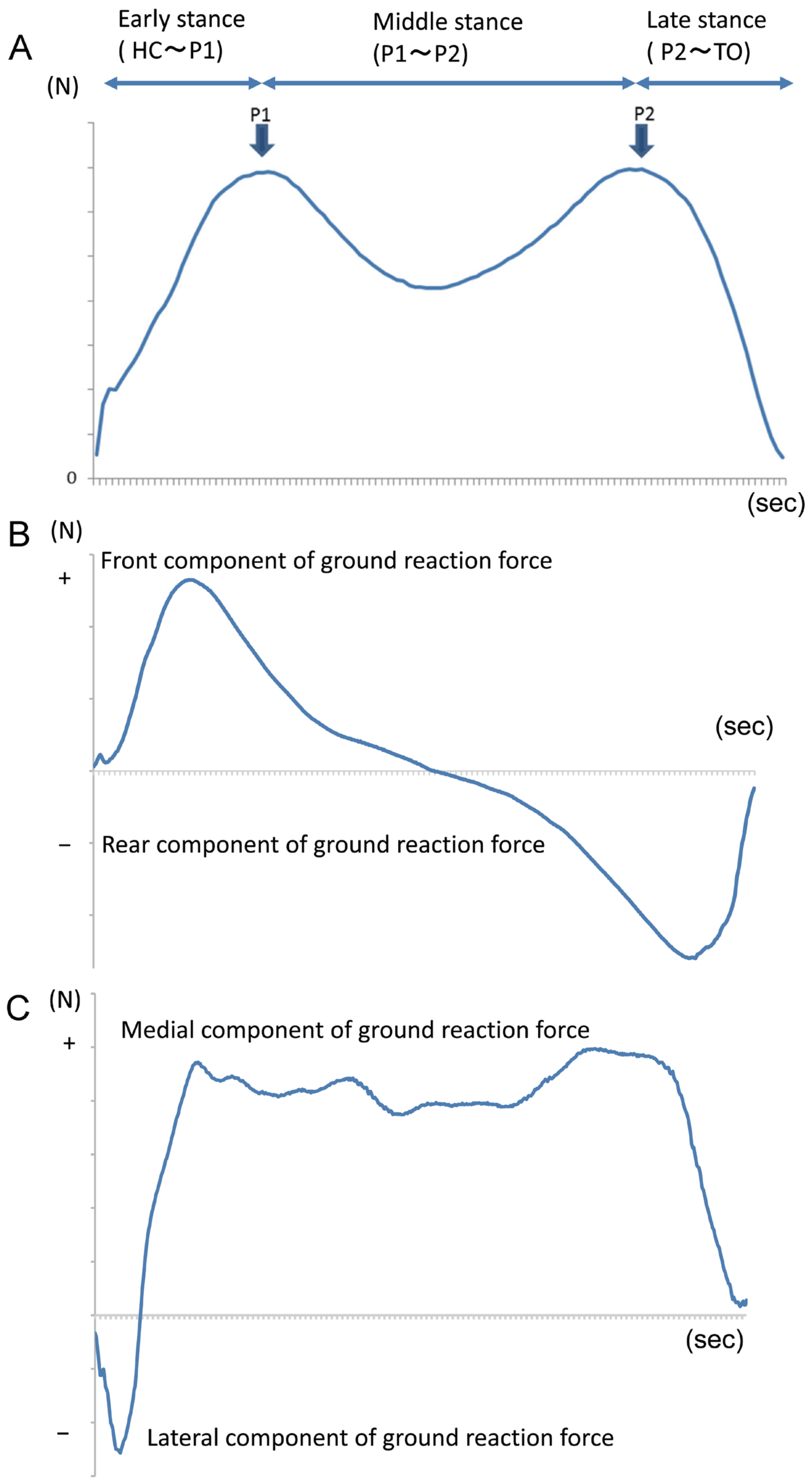

Fig. 1 (A) Definition of gait phases based on the vertical component of the ground reaction force. The first peak of the vertical component was defined as P1 and the second as P2. The stance phase was divided into the following three phases: early, from heel contact (HC) to P1; middle, from P1 to P2; 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.

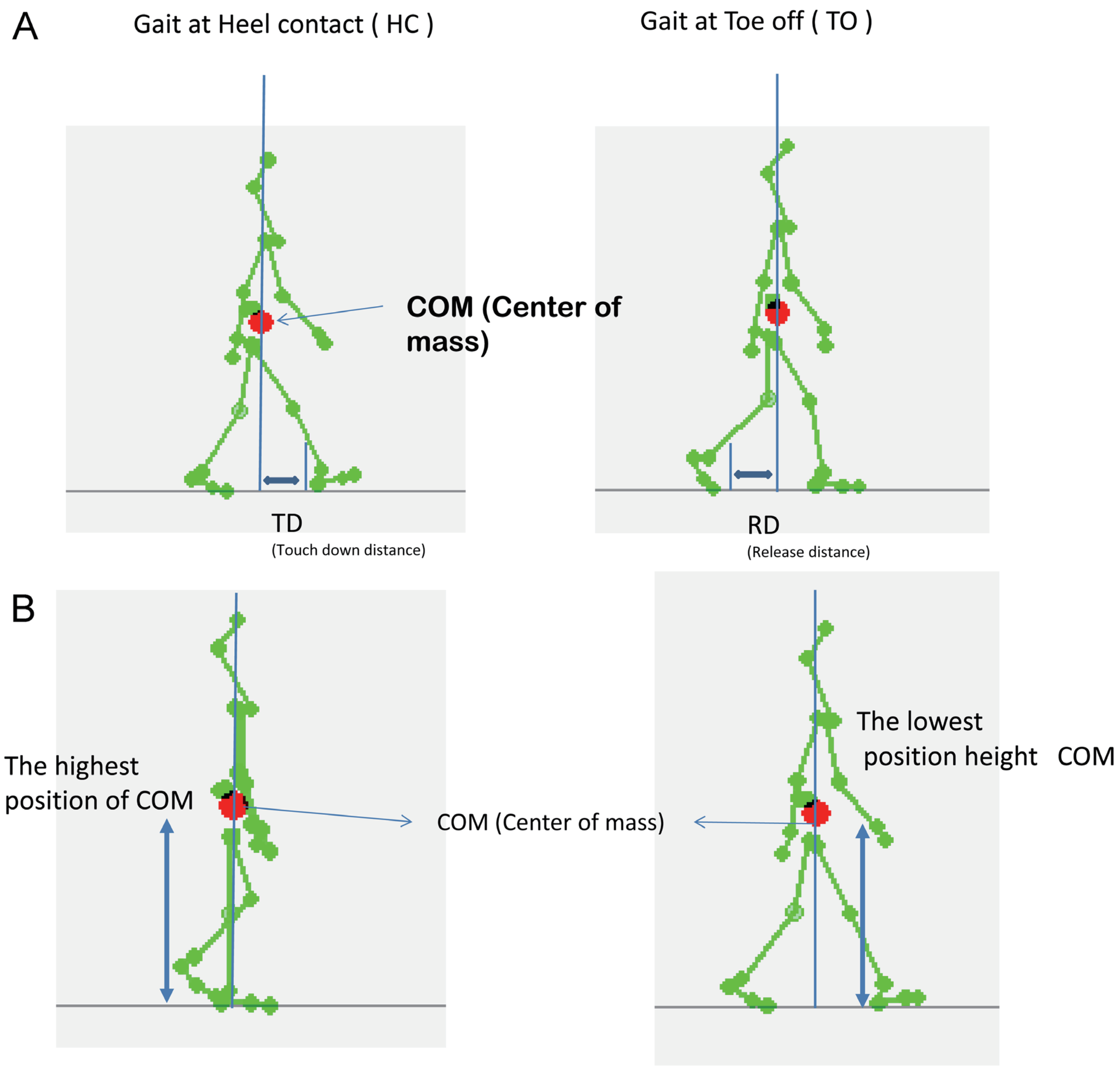

Fig. 2 (A) Definitions of the touchdown distance (TD) and the release distance (RD) indices using the body's center of mass (COM) during gait. TD is the distance between the heel contact point and COM at the moment of touchdown. RD is the distance between the COM and the toe of the releasing foot at 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.

extremity. The distance between the heels during the double stance phase was defined as the step width. The touchdown distance (TD)[15)] 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[16)] at the moment of foot touchdown. The release distance (RD)[15)] 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[16)] were used to calculate the COM position at each point. The highest and lowest 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 ± 6.7° and that of the control group was 6.3 ± 3.9°. The average foot length and foot width were 22.2 ± 1.0 and 8.2 ± 0.6 cm, respectively, in the hallux valgus group and 21.2 ± 1.2 and 8.2 ± 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 ≥15° 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 N·s, middle stance: P=0.03, 95%CI: 3.4–16.3 N·s, late stance: P=0.03, 95%CI: 2.8–6.7 N·s) and in the Z-direction for the late stance phase (P=0.04, 95%CI: 57.4–158.9 N·s)

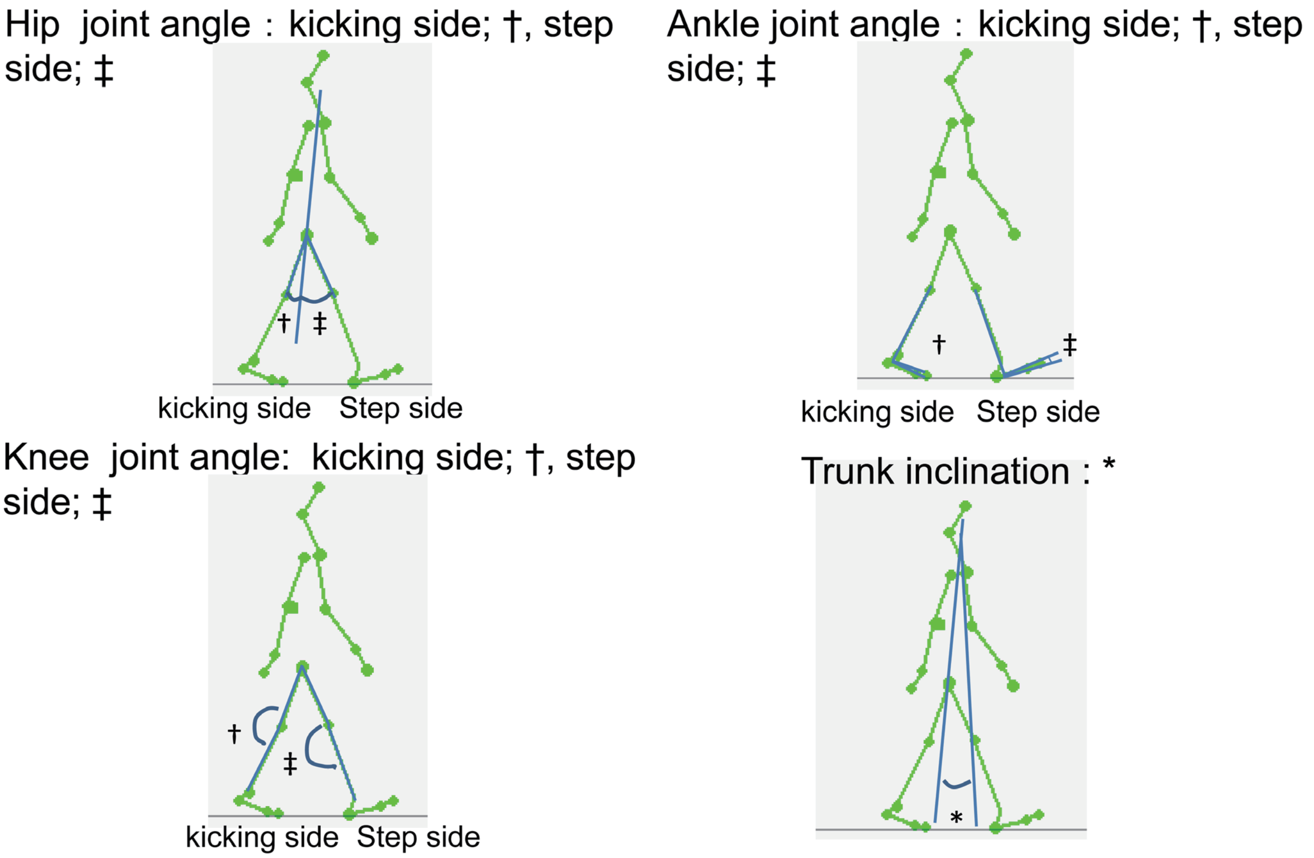

Fig. 3. Definitions of the joint angles and trunk inclination during gait. These angles were measured on both the step and kicking sides at heel contact, P2 peak, and toe-off.

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 (n=10)	0.9±0.1	36.8±7.0	4.4±2.2	16.5±4.1	17.9±4.7
Control group (n=10)	1.2±0.1 **	39.9±2.6 *	4.3±3.2	19.3±1.8 *	17.8±2.8

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.

(**Table 1**). 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=0.01, 95%CI: 0.58–1.47 m/s), as did the step length (P=0.02, 95%CI: 19.7–38.3 %) and TD (P=0.03, 95%CI: 8.3–17.4 %) (**Table 3**). Furthermore, the highest COM level was 53.7 ± 1.6% in the hallux valgus group and 52.1 ± 1.3% in the control group; the lowest COM level was 52.8 ± 1.5% in the hallux valgus group and 50.6 ± 1.3% in the control group. Consequently, the difference between the maximum and minimum heights was 0.8 ± 0.3% in the hallux valgus group and 1.5 ± 0.4% in control group. The COM in participants in both groups reached similar maximum positions. However, participants in the hallux valgus group achieved less difference between the highest and lowest COM position (P=0.03, 95%CI: 0.38–0.87%). In the hallux valgus group, the trunk inclination angles during gait showed a significant increase at HC (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 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	Step side	Kicking side
Hallux valgus group (n=10)	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 (n=10)	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.

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.7) 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 represents decreased medial longitudinal arch function. Therefore, the function of the inner longitudinal arch should be improved. Lower limb joint angle measurements showed a decrease in ankle dorsiflexion in the hallux valgus group at the point of maximum vertical component at P2. Consequently, ankle dorsiflexion does not occur during the late stance phase, thereby restricting the anterior inclination of the lower leg. Furthermore, during gait, the anterior trunk inclination in the hallux valgus group was greater than that of the control group. It is presumed that there is a kyphosis of the spine because inclination of the trunk continues throughout gait. Excessive forward (anterior) tilt during late stance resulted from limited ankle dorsiflexion to compensate for the forward movement of the COM. Therefore, RD shortening was not observed because this trunk inclination in the hallux valgus group increased the distance between the hind leg and COM during gait. Consequently, the reduction in gait speed can be attributed to the shortened TD, whereas RD was unchanged. In the hallux valgus group, the pelvis tilted backward with the flexion of the trunk; therefore, it is inferred that there was no difference in RD because this extension restriction of the hip joint and the forward tilt of the lower leg decreased. In other words, TD should be extended to improve the step length of patients with hallux valgus. Moreover, TD should be prolonged to improve the range of hip extension and ankle dorsiflexion in the middle to late stance phases. Normal free gait requires ankle dorsiflexion of approximately 10° and plantar flexion of approximately 20°.17) The hallux valgus group had an ankle dorsiflexion of ≤10° at peak P2. Therefore, the ankle dorsiflexion range should be improved to promote gait speed and efficiency as well as for TD extension and to control and prevent the progression of hallux valgus.

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 people18) who underwent total knee replacement19) or total hip arthroplasty.20) 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.21) 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 [REMOVED DUE FIELD]in subjects with higher hallux valgus angles.22) 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.6) 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.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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