INTRODUCTION

People with bilateral transtibial amputation (BTTA) can learn bipedal walking using bilateral transtibial prostheses, although they require more training than those with unilateral transtibial amputation (UTTA), who can compensate for their limb loss with their intact limb. Given that BTTA is rare, there are fewer reports on walking for people with BTTA than for people with UTTA. Therefore, clinicians have limited information about how people with BTTA can achieve stable walking, which hinders systematic intervention for walking after BTTA.

The ability to walk with lower limb prostheses is known to be affected by age, sex, amputation level, skin condition, contracture, muscle strength, and balance ability. When walking with prosthetics, the characteristics and performance of prosthetic components also influence walking performance. People with UTTA have reduced stability
caused by limited afferent feedback from their lower limb and limited ankle joint mobility.9–11 Previous studies have reported that walking in people with UTTA is characterized by decreased stability in the stance phase, asymmetric walking, and increased energy consumption.12,13) Therefore, the purpose of physical therapy for most people with UTTA is to reduce asymmetry. However, people with BTTA might walk with a strategy that is different from that used by people with UTTA because those with BTTA do not have a healthy limb. Therefore, physical therapy for people with BTTA may require an approach that is different from therapies used for those with UTTA.

Trunk kinematics is important for walking assessment, and compensation for trunk kinematics and trunk muscle activity occurs in people with lower limb disabilities.14,15) In previous research focusing on trunk movement in people with UTTA, trunk lateral excursions increased with increasing level of amputation, and in the transfemoral amputees, trunk flexion-extension excursions increased.16) Many previous studies have examined the relationship between walking speed and trunk activity in people with UTTA.17–19) Hendershot et al. reported that the trunk muscle forces and spinal loads increased with increasing walking speed in persons with lower limb amputation when compared with able-bodied controls.17) In another study, stride length asymmetry was shown to be dependent on the combination of asymmetries in forward foot placement and trunk progression, with a smaller contribution of trunk-progression asymmetry at slow speed.19) Altered trunk motion and spinal loading may contribute to increased risk of low-back injury among lower limb amputees.16) In people with UTTA, an increase in trunk muscle activity and trunk-pelvic movement patterns suggested an increase in the spinal load contributing to elevated risk of low-back pain.17) Decreased trunk flexion angle and increased trunk lateral bending may cause secondary low-back pain when a prosthetic leg is used over a long period.17,20)

Previous research has reported that people with BT TA have a symmetrical walk, decreased walking speed, increased step width, and increased energy consumption during walking when compared with able-bodied controls.21,22) In a comparison of people with BT TA and able-bodied participants walking at similar speeds, the BT TA group demonstrated decreased ankle dorsiflexion and knee flexion in the stance phase, decreased peak ankle internal plantar flexion moment, decreased ankle power generation, and increased bilateral hip hiking when compared with able-bodied participants.21) It is necessary to understand the compensatory movements unique to people with BT TA and to carry out rehabilitation with consideration for the prevention of low back pain and secondary disorders. In a previous study focusing on trunk movement in people with BT TA, it was reported that the trunk lateral flexion angle and forward trunk lean increased during walking when compared with able-bodied participants at similar walking speed and the degree of lean was directly proportional to speed.22) However, there are only a few studies that have examined the influence of trunk angle change and walking speed.22) As with people with UTTA, it is important to understand the compensatory motion used by people with BT TA when walking. Understanding trunk compensation during walking in people with BT TA may contribute to the planning of optimal physical therapy and prevention of secondary disorders. Therefore, this study aimed to clarify the changes in trunk lateral bending and trunk flexion angle during walking in people with BT TA.

MATERIALS AND METHODS

Ethical Considerations

All participants gave their informed consent. This study was approved by the Ethical Review Board of the National Rehabilitation Center for Persons with Disabilities (Approval number: 28-149, 1 March 2017).

Participants

In this cross-sectional study, four participants with BT TA (BT TA group) who could walk without upper-limb walking aids (mean [standard deviation, SD]; age, 31.5 [17.1] years; height, 175.4 [2.8] cm; mass, 69.8 [5.3] kg) and ten able-bodied participants (control group) (age, 23.6 [3.3] years; height, 173.1 [4.0] cm; mass, 65.2 [10.4] kg) were recruited by convenient sampling. The characteristics of the BT TA group are presented in Table 1. None of the participants had cognitive dysfunction, skin disorders (e.g., wounds, pain, sensory disorders), or an extremely short residual limb that would make it difficult to wear a prosthesis. The data were measured from June 2017 to November 2017.

Experimental Protocol

All participants wore shoes during the measurements. Retroreflective markers were attached to the participant according to a modified Helen Hayes marker set.23,24) On the shoes, a marker was affixed to a position corresponding to an anatomical landmark, and prostheses were affixed to positions corresponding to healthy participants. All participants walked along the 10-m walkway at a comfortable speed.
and at maximum speed. For the monitoring of comfortable-speed walking and maximum-speed walking, the following respective instructions were given: “Please walk at a normal comfortable speed,” and “Please walk at the fastest speed.” After one practice trial, ten walking trials were recorded for each participant. Participants were first instructed to walk at a comfortable speed and then at maximum speed. Participants could rest at any time during the experiments. Ten gait cycles with clean heel strikes on one of the eight force plates without apparent acceleration and deceleration were used for the kinematic analysis.

**Data Collection**

Walking analysis was performed using a 12-camera three-dimensional motion analysis system (MAC3D; Motion Analysis, Natick, MA, USA) with eight Kistler force plates, using Cortex software (version 3.6, Motion Analysis). The sampling rate was set at 100 Hz for the cameras and the force plates. The collected data were processed using Visual3D software (version 4.96, C-Motion, Germantown, MD, USA). The marker trajectories were filtered using a fourth-order, zero-lag Butterworth filter with cutoff frequencies of 6 Hz. Trunk flexion-side bending angles (with respect to the ground) and temporospatial parameters were calculated for each gait cycle using the trunk and foot markers and the force data.

The primary outcomes were the trunk lateral bending range and the average trunk flexion angle during one gait cycle relative to the ground. The trunk lateral bending range was defined as the range of left–right side bending movement values within a gait cycle. Trunk flexion angle was defined as the average value of the trunk flexion angle during a gait cycle.

The secondary outcomes were walking speed, step width, cadence, stride length, and double support time. The stride length was defined as the sum of the left and right stride lengths. For other gait parameters, the average value of each measurement item was extracted as a representative value for each participant. This study compared the average value of each variable between the BTTA group and the control group.

**Statistical Analysis**

All statistical analyses were conducted using SPSS Statistics version 24.0 (IBM, Armonk, NY, USA). Each measurement item between the BTTA group and the control group were compared using the Mann–Whitney U test. The threshold for significance was set at P<0.05.

**RESULTS**

In the maximum-speed walking test, the median (minimum–maximum) walking speed was significantly lower in the BTTA group than in the control group (1.78 [1.63–1.95] vs. 2.14 [2.00–2.60] m/s, P=0.002). The double leg support time was significantly greater in the BTTA group than in the control group (0.18 [0.15–0.21] vs. 0.12 [0.06–0.16] s, P=0.008). There were no significant differences between the BTTA group and the control group regarding stride length (1.59 [1.36–1.73] vs. 1.76 [1.60–1.95] m), cadence (142.03 [112.99–151.13] vs. 150.77 [129.03–172.41] steps/min), and step width (0.13 [0.12–0.15] vs. 0.12 [0.09–0.15] m) (Table 2).

In the comfortable-speed walking test, there were no significant differences between the two groups for all parameters. The median (minimum–maximum) walking speed...
DISCUSSION

This study examined the walking characteristics of people with BTTA, such as trunk movement, according to the walking speed. The BTTA group tended to walk slower with an increased double leg support time and a smaller trunk flexion during maximum-speed walking when compared with the able-bodied controls. The difference between the two groups was greater during maximum-speed walking than during comfortable-speed walking. The results showed that the median values of the trunk flexion angle decreased during maximum-speed walking.

The decrease in the trunk flexion angle in the BTTA group was observed throughout one gait cycle, which indicates that the BTTA group walks with their trunk upright. Theoretically, people with BTTA using passive prosthetic feet have to rely more on hip flexors for swing initiation than able-bodied people who can rely on plantar flexors and hip flexors.25) Posterior pelvic tilt relative to the femur, induced by an upright trunk, lengthens hip flexor muscles, which would facilitate force generation according to the force–length relationship of the muscles. This mechanism would contribute to better gait performance in people with BTTA.

Previous studies have reported that trunk lateral bending

Table 2. Maximum-speed walking parameters

| Outcome measures                  | Control group (n=10) | BTTA group (n=4) | P-value | BTTA 1 | BTTA 2 | BTTA 3 | BTTA 4 |
|-----------------------------------|---------------------|------------------|---------|--------|--------|--------|--------|
| Walking speed (m/s)               | 2.14 (2.00–2.60)    | 1.78 (1.63–1.95) | 0.002   | 1.63   | 1.85   | 1.95   | 1.71   |
| Step width (m)                    | 0.12 (0.09–0.15)    | 0.13 (0.12–0.15) | 0.304   | 0.15   | 0.12   | 0.12   | 0.14   |
| Stride length (m)                 | 1.76 (1.60–1.95)    | 1.59 (1.36–1.73) | 0.054   | 1.73   | 1.63   | 1.56   | 1.36   |
| Cadence (steps/min)              | 150.77 (129.03–172.41) | 142.03 (112.99–151.13) | 0.188 | 112.99 | 134.98 | 149.07 | 151.13 |
| Double leg support time (s)       | 0.12 (0.06–0.16)    | 0.18 (0.15–0.21) | 0.008   | 0.21   | 0.17   | 0.15   | 0.19   |
| Trunk lateral bending (°)         | 4.73 (3.08–6.47)    | 5.71 (4.50–7.91) | 0.304   | 7.91   | 5.37   | 6.05   | 4.50   |
| Trunk flexion angle (°)           | 4.79 (0.02–8.01)    | 1.75 (0.18–2.64) | 0.036   | 2.44   | 2.64   | 1.07   | 0.18   |

Data shown as median (minimum–maximum) for groups and as mean values for BTTA participants.
increased during the prosthetic stance phase in people with UTTA,\textsuperscript{16,26} However, in the current study, there was no left–right asymmetry in the BTTA group. A previous study of people with UTTA found that increased trunk lateral bending toward the amputation side compensated for reduced hip abductor moment.\textsuperscript{26} People with BTTA have been reported to walk symmetrically with a slower walking speed, greater step width, and higher energy consumption than able-bodied controls.\textsuperscript{21,22} In the present study, the BTTA group had a slower walking speed than the control group during maximum-speed walking but the step width was not significantly different from the control group. The trunk lateral bending results in this study were not significantly different between the two groups. Our participants and those in the previous studies differ in age (mean [SD]: 31.5 [17.1] years vs. 52.8 [17.6] years\textsuperscript{21} and 50 [18] years\textsuperscript{22}), which might have contributed to the difference in the results regarding step width. In addition, the absence of a healthy side in people with BTTA may have prevented the observation of trunk asymmetry in the frontal plane. This study also measured the maximum-speed walking conditions to make it easier to observe the compensatory movement of the BTTA group.

For people with UTTA, a goal is to walk with less left–right asymmetry, but this is not the case for people with BTTA. In this study, the BTTA group showed a decrease in trunk flexion angle without a significant difference in trunk lateral bending. The results of this study differed from those of the previous study.\textsuperscript{22} Differences in the age of the participants, causes of amputation, and faster walking speeds may explain the different results. Additionally, no significant difference was observed between people with BTTA and able-bodied controls in comfortable-speed walking. This result may be due to recent developments in prosthetic rehabilitation, or because the participants in the BTTA group in our study were younger and lacked vascular amputees, in contrast with previous studies.\textsuperscript{21,22} Trunk flexion angle may be an important indicator when evaluating the gait compensation for people with BTTA, and maximum-speed walking is required to detect any changes in their trunk flexion angle. The results of this study may contribute to the design of rehabilitation programs and goal setting for people with BTTA.

This study has some limitations. This study recruited only four participants with heterogeneous characteristics: the age and the cause of amputation could not be controlled. It should be noted that these results are generalized, and this study only considers the tendencies for BTTA in medically stable people. However, the data are valuable because the BTTA group was composed of participants from the general population, rather than military participants, and amputations in some participants were due to diseases. Further gait analysis studies with larger sample sizes or with electromyographic data collection would help confirm the relationship between
the walking kinematics and secondary musculoskeletal disorders in people with BTTA. In the future, it will be necessary to examine how physical therapy interventions for people with BTTA affect trunk movement and the frequency of secondary disorders caused by long-term use of prostheses.

CONCLUSION

There were no significant differences in gait parameters between the BTTA group and the control group during comfortable-speed walking, but differences in walking speed, double leg support time, and trunk flexion angle were observed during maximum-speed walking. It is suggested that when the BTTA group walks fast, the trunk stands upright more than when walking at comfortable speed. When evaluating the gait compensation for people with BTTA, trunk flexion angle may be an important index and maximum-speed walking is needed to detect their trunk flexion angle change.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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