Investigation of balance strategy over gait cycle based on margin of stability

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ABSTRACT

This study was conducted to investigate the balance strategy of healthy young adults through a gait cycle using the margin of stability (MoS). Thirty healthy young adults participated in this study. Each performed walking five times at a preferred speed and at a fast speed. The MoS was calculated over a gait cycle by defining the base of support (BoS) changes during a gait cycle. The MoS was divided into medial/lateral and anterior/posterior components (ML MoS and AP MoS). The central values and the values at 12 gait events of the MoS were compared. Positive/negative integration of ML MoS (ML MoS$_{POS}$ and ML MoS$_{NEG}$, respectively) and the average ML/AP MoS over a cycle (ML/AP MoS$_{mean}$) were significantly lower at a fast gait than at a preferred gait. ML/AP MoS were lower at a fast speed than at the preferred speed, except for the ML MoS immediately before left heel strike (pre left HS) and right and left heel strike (HS). ML/AP MoS were significantly lower immediately before heel strike (pre-HS) than in other gait events, regardless of walking speed. It was suggested that pre-HS is the most unstable moment in both ML/AP directions and a crucial moment in control of gait stability. The results presented above might be applicable as basic data regarding dynamic stability of healthy young adults through a gait cycle for comparisons with elderly people and patients with orthopedic disorders or neurological disorders.

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1. Introduction

The World Health Organization (2008) has reported that about 28–35% of people aged 65 years and older experience falls every year, and the rate increases up to about 32–42% for people aged 70 years and older. Falls can change elderly peoples' prognosis greatly, since a fracture might lead to a state requiring long-term care or might even lead to death. In 2015, there were approximately 226 million falls (GBD, 2016a), which resulted in the death of 527,000 people (GBD, 2016b). Reportedly, 50% of the falls of middle-aged and elderly people occur during walking (Li et al., 2006), so that a gait disorder and balance disorder are strongly related to the risk factors for falls (Tinetti and Kumar, 2010). It is important to identify persons at risk of falling due to an unstable gait also from the viewpoint of fall prevention. Several methods have been proposed by which stability during walking is evaluated (Bruijn et al., 2013).

Measures for analyzing dynamic stability during walking include the margin of stability (MoS). This index of dynamic stability takes the "ground state of feet" into consideration, as proposed by Hof et al. (2005). It has been demonstrated to have construct validity and predictive validity at a certain level (Bruijn et al., 2013). Other typical measures include the Lyapunov exponent by nonlinear analysis (Dingwell et al., 2000). Although it evaluates stability with time series kinematic data of body segments (e.g., trunk) and joint angles (e.g., knee), the MoS assesses dynamic stability at certain gait events. The benefits of the MoS include ease of comparing dynamic stability at a gait event among individuals, and individual dynamic stability can also be compared between gait events.

Recently, MoS-related studies have been flourishing. Studies of elderly people (Arvin et al., 2016; Mademli and Arampatzis, 2014), stroke patients (Vistamehr et al., 2016; Punt et al., 2017), Parkinson's patients (Peterson and Horak, 2016a, 2016b), as well as of young people, are increasingly being conducted (Sivakumaran et al., 2018; Lugade and Kaufman, 2014). Many studies have compared the MoS at certain gait events (e.g., at heel strike (HS)) (Sivakumaran et al., 2018; Peebles et al., 2016), at midstance

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(MS) (Peebles et al., 2016)), or at the minimum of the MoS (Sivakumaran et al., 2018), but few reports in the relevant literature have accurately compared MoS values over a gait cycle. Additionally, to simplify the boundary line of the base of support (BoS) for calculating the MoS, some studies have been conducted under the assumption of an invariant BoS boundary or no medial BoS boundary through a gait cycle.

The primary objective of this study was to provide basic data of the MoS over a gait cycle in healthy young adults. The second objective was to investigate the gait strategy of healthy young adults in terms of dynamic stability. Two conditions of walking, at a preferred speed (preferred gait) and at top speed (fast gait), were chosen as gait conditions. A fast gait is reproducible and reliable as a walking speed measure (Bohannon, 1997), and it is susceptible to individual static and dynamic balance function in elderly people (Ikai et al., 2006). Flat ground walking was chosen as the measurement environment because it is considered that a more natural gait is measurable in flat ground walking than in treadmill walking based on many discussions about differences in the kinematics data of both gaits (Alton et al., 1998).

2. Methods

2.1. Participants

Thirty healthy young adults (14 male, 16 female) participated in this research. Their average age, height, and mass were 21.2 ± 0.8 years, 1.65 ± 0.08 m, and 58.6 ± 1.0 kg, respectively. Persons with a history of orthopedic disorders or neurological disorders that would influence balance were excluded.

This study was conducted with the approval of the Ethics Committee of Yamagata Prefectural University of Health Science (approval number: 1809–14). The contents of this study were explained verbally and in writing to participants before measurements, and their written, informed consent was obtained.

2.2. Equipment

A three-dimensional motion analysis system (VICON Nexus, Vicon Motion Systems, Oxford, UK) equipped with eight infrared cameras with a sampling frequency of 200 Hz was used for kinematics data measurement during flat ground walking. A Plug-In Gait Full-Body was adopted as a marker model. A total of 35 reflective markers were attached to the body. Furthermore, four reflective markers were appended over the first and fifth metatarsal heads (1MTP and 5MTP) on the left and right sides, respectively, for derivation of the BoS coordinates. Additional markers were placed such that the centers of their spheres might pass along the medial and lateral borders of the feet when in a natural standing position.

2.3. Data collection

A straight, approximately 10-m-long walkway was prepared for the experiment. Preferred and fast gait speeds were selected as the walking conditions. Participants were asked to practice in advance of measurement until they became accustomed to the walking conditions. They were verbally instructed to "walk at a comfortable pace" at a preferred gait and to "walk as fast as possible" at a fast gait during the experiment. Five measurements were conducted for each condition. The center portion of the walkway, where a steady speed was implemented, was set as a target range. Data from a right HS to immediately before the next right HS were adopted as the analysis range. The participants walked along the Y-axis of the laboratory coordinate system. With respect to the traveling direction, the right direction is the positive direction on

the X axis, and the upward direction is the positive direction on the Z axis.

2.4. Data analysis

The timings of HS and toe off (TO) in a gait cycle were found by the vertical components of the speed of the midpoint of a heel marker and the second metatarsal head (2MTP) marker (O'Connor et al., 2007). Foot flat (FF) was defined as the time point when the anterior velocity of 2MTP fell below 100 mm/s (Ghoussayni et al., 2004); MS was then set at a time point when the center of mass (CoM) overtakes the ankle marker on the stance limb along the Y-axis (Lee and Farley, 1998). Heel off (HO) was defined to occur when the vertical coordinate of a heel marker became greater than that at FF by 10 mm or more. The data one point before the timing of HS were used as pre-HS. The timing of FF is often after TO at the preferred gait but might be before TO at the fast gait. Three-dimensional coordinate data were filtered using a fourth-order, low-pass, zero-lag Butterworth filter with a 6-Hz cut-off frequency.

The X coordinates of CoM at the first and second right HS were adjusted to correct the deviation of the Y-axis of the laboratory coordinate system and the walking direction. The correction was conducted by multiplying the XY coordinates used for analysis by a two-dimensional rotation matrix with the XY coordinates of the CoM at the second right HS as a center.

Dynamic stability during walking was calculated using the MoS and the extrapolated center of mass (XcoM) by Hof et al. (2005). MoS and XcoM are given by

$$MoS = U_{max} - XcoM \tag{1}$$

$$XcoM = x + v/\omega_0 \tag{2}$$

MoS is given as the shortest distance between U_{max} (i.e., BoS boundary) and XcoM, as shown in Eq. (1) and Fig. 1, where XcoM denotes the extrapolated center of mass and represents CoM with
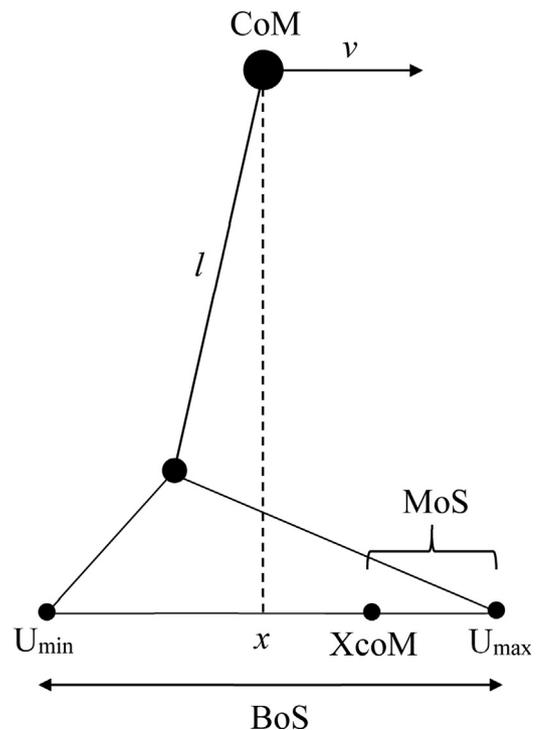

Fig. 1. Inverted pendulum model. CoM maintains balance on the pendulum of length *l*. *x* is the vertical projection of CoM, and *v* is the anterior velocity. MoS is the distance between XcoM, considering *v*, and U_{max}, the BoS boundary.

the factor of speed appended. Calculation of XcoM was conducted as shown in Eq. (2) and as discussed later. In the present study, virtual markers, including the Toe, H, H_{med}, and H_{lat} markers, were determined by calculation (see Fig. 2 for details). Reflective markers (2MTP and heel) were used with reference to a Plug-In Gait Full-Body model for calculation of virtual markers. An H marker is a point that extends the marker radius and the length of the base from the heel marker to the 2MTP marker. A toe marker was defined as the distal end of the toes using the measured foot length along the vector defined by the 2MTP and H markers. An H_{med} marker and an H_{lat} marker were placed at the medial and lateral points, respectively, of a heel distant from an H marker by a calcaneus width. The calculation was based on Lugade et al. (2011). The one-foot BoS boundary was determined by the toe, 1MTP, 5MTP, H_{med}, and H_{lat} markers (Fig. 3). The foot length and calcaneus width on both sides were measured in advance of the experiment. The one-foot BoS consisted of H_{med} and H_{lat} markers from HS to before FF, of the H_{med}, H_{lat}, 1MTP, 5MTP, and toe markers from FF to before HO, and of the 1MTP, 5MTP, and toe markers from HO to before TO during the stance phase. Then, the constructed one-foot BoS was combined on both feet to obtain the BoS that changes over a gait cycle (Fig. 4). The BoS boundary was divided into ML and AP components. Furthermore, a program was created to automatically select the marker corresponding to the ML/AP BoS boundary (U_{max}, U_{min}) over a gait cycle (Fig. 5). Here, x and v in Eq. (2) respectively denote the position and velocity of CoM. v was found using a first order central difference formula of x time series. ω_0 denotes the natural angular frequency of the pendulum used in the model ($\omega_0 = \sqrt{g/l}$), g represents gravitational acceleration ($g = 9.81$ m/s^2), and l is the distance from CoM to the axis of rotation. For this study, l was defined as the distance on a sagittal
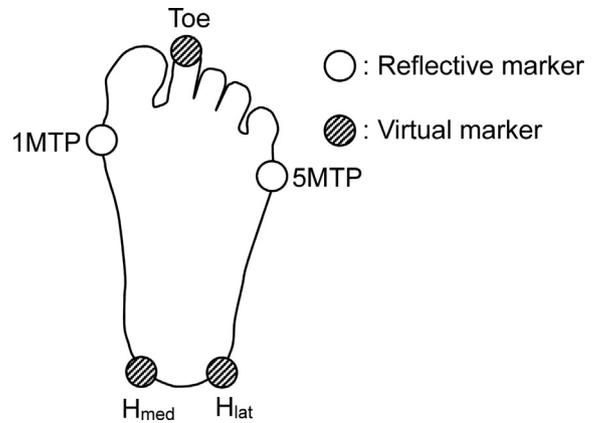

Fig. 3. Foot BoS defined by markers (example of a right foot viewed from above). Virtual marker coordinates were determined based on real marker coordinates. Five points in the figure were set up as boundary points of foot BoS.

plane or a frontal plane from an H marker to CoM during a gait cycle, a value that changes during a gait cycle. The sagittal and frontal l values were used to calculate AP MoS and ML MoS (described later), respectively.

The MoS was also calculated separately in this study as ML MoS and AP MoS. A program was prepared so that the MoS would be determined as the shortest distance between XcoM and a BoS boundary after judging whether XcoM was outside (negative value) or inside (positive value) the BoS (see Fig. 5 for details).

Spatial-temporal gait parameters included the walking speed, cadence, step length, and step width over a gait cycle. Walking
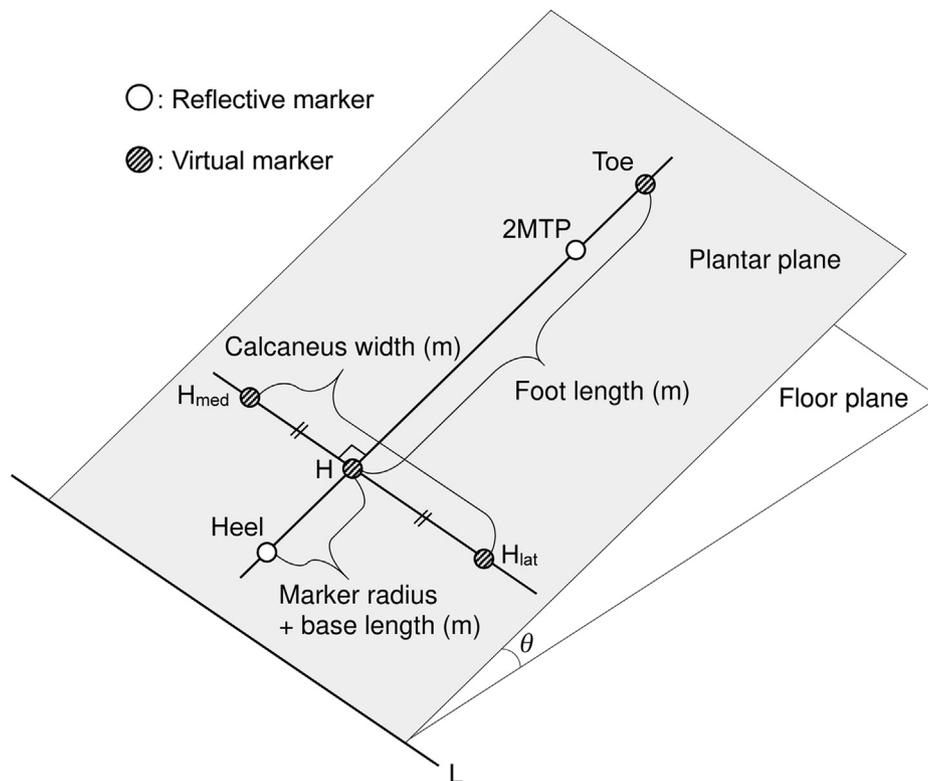

Fig. 2. Virtual marker calculations (example for the right foot). Set the plantar plane as a two-dimensional plane rotated θ from the Floor plane around the L axis. Virtual markers are assumed to be on the plantar plane. The H marker is a point that extends the marker radius and the length of the base from the heel marker to the 2MTP marker. The toe marker is a point that extends the foot length from the H marker to the 2MTP marker. Next, consider a line in which the line connecting the heel maker and the 2MTP marker is orthogonal to the H marker. The H_{med} marker is the point extending inward a half calcaneus width from the H marker, and the H_{lat} marker is the point extending outward.
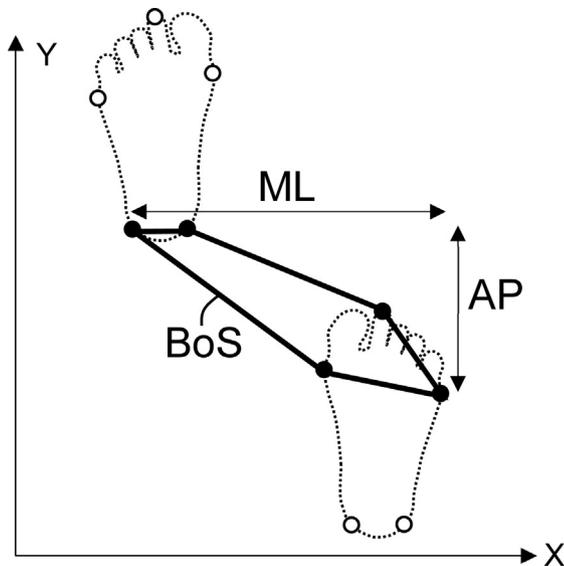
Fig. 4. Example of BoS on the X-Y plane. The figure shows the moment of the left HS after the right HO.

speed was taken as the average AP CoM velocity. The step length and step width were found as the average of values for the right and left foot, calculated respectively as the distance between AP and ML to the heel marker at each HS (Table 2) (Elble et al., 1991). In addition, ML/AP MoS was normalized by the length of the lower limb (spina malleolar distance) (Hallemans et al., 2018). When XcoM is inside of BoS (MoS is positive), it is in a dynamically stable state, and when XcoM is outside of BoS (MoS is negative), it is in a dynamically unstable state (Hof et al., 2005). Therefore, ML MoS_{POS} and ML MoS_{NEG} were used as indices representing the phase and degree of stability and instability. ML MoS_{POS} and ML MoS_{NEG} were determined by time integration (a gait cycle as 1.0) of positive and negative values of ML MoS, respectively (Fig. 6A). The values of ML/AP MoS were averaged over a gait cycle (ML/AP MoS_{mean}). Furthermore, the values of MoS at 12 gait events of the cycle were calculated for ML/AP MoS at a preferred/fast gait to elucidate the influence of walking speed and cycle on MoS.

2.5. Statistical analysis

Five walking trials were averaged for each gait for data analysis. The normality of each parameter of a preferred and fast gait was verified using Shapiro-Wilk tests. These two conditions were compared using the Wilcoxon signed-rank test or the paired *t*-test to compare their characteristics. Main effects by gait event factors and speed factors and each interaction were investigated using two-way repeated measures ANOVAs for comparison of ML MoS and AP MoS between gait events. A multiple comparison procedure was performed between factors as a post hoc test for cases with a significant difference in main effects, whereas a simple main effect test was applied for cases with interaction. Statistical analyses were carried out using R version 2.8.1. The level of significance was set at $p < 0.05$.

3. Results

Walking speed, cadence, step length, and step width were significantly greater for a fast gait than for a preferred gait (Table 1). Fig. 6 presents an example of ML/AP MoS at a preferred gait and a fast gait. The results showed that ML MoS_{POS}, ML MoS_{NEG}, and
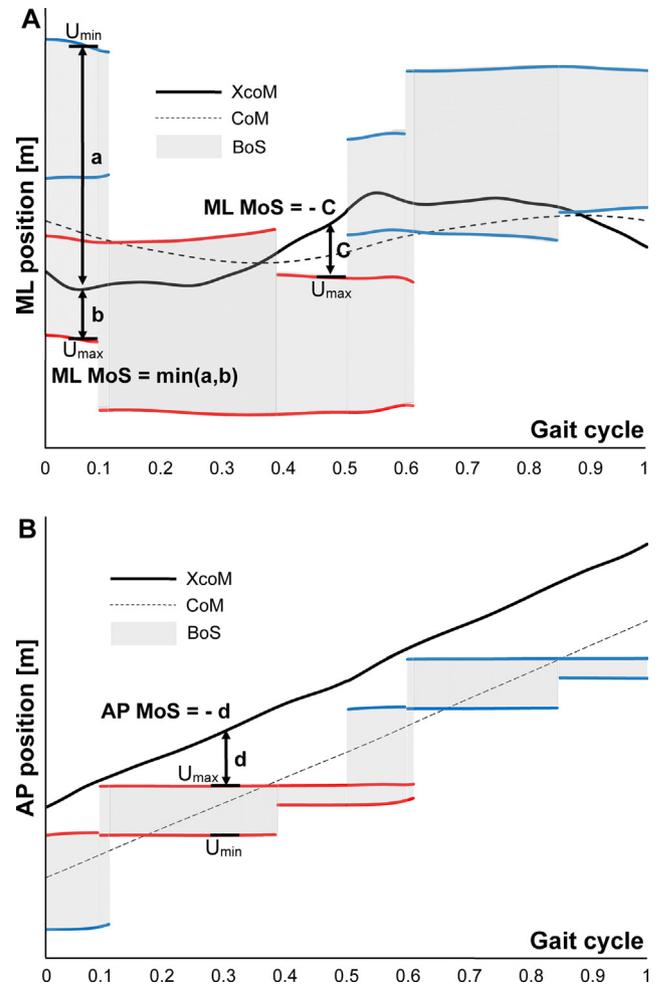

Fig. 5. An example showing how BoS and XcoM change over a gait cycle. A represents a change in ML position, and B represents a change in AP position. The red and blue lines represent markers corresponding to the BoS boundary of the right and left feet, respectively. The right HS is 0, and the left HS is approximately 0.5 in the gait cycle. 0 to 0.1 and 0.5 to 0.6 are double-support phases, and 0.1 to 0.5 and 0.6 to 1 are single-support phases on the right and left, respectively. This figure corresponds to Fig. 6AB. A: An example of an ML MoS at 0 to 0.1 is after the right HS. Here, U_{max} corresponds to the right H_{lat} marker, and U_{min} corresponds to the left 5MTP marker. When two (a, b) ML MoS can be selected, the smaller one "b" is selected. In the case of c (0.4 to 0.5), ML MoS is calculated as "-c" as a negative value, because XcoM is outside BoS. B: An example of AP MoS at 0.3 is right single-support (before right HO). Here, U_{max} corresponds to the right Toe marker, and U_{min} corresponds to the right H_{lat} marker. In this trial, AP MoS is negative over a gait cycle, because XcoM always precedes U_{max}.

ML/AP MoS_{mean} were significantly lower at a fast gait than at a preferred gait (Table 2).

Fig. 7 shows a comparison of ML/AP MoS at 12 gait events and at walking speed. Both main effects were significant in the comparison of ML MoS (gait event – F = 126.8, $p < 0.001$; speed – F = 143.3, $p < 0.001$). The interaction was also found to be significant (F = 49.04, $p < 0.001$). Furthermore, both main effects were significant in the comparison of AP MoS (gait event – F = 1174, $p < 0.001$; speed – F = 258.3, $p < 0.001$). The interaction was also found to be significant (F = 98.47, $p < 0.001$). In the comparison by the speed factor, at all gait events, ML/AP MoS were lower at a fast speed than at the preferred speed, except for the ML MoS at the pre left HS and the right and left HS. In contrast, ML MoS was higher at a fast speed than at the preferred speed at the right and left HS. In the comparison by the gait event factor, ML MoS at pre right and left HS were significantly lower than the ML MoS at other gait events, regardless
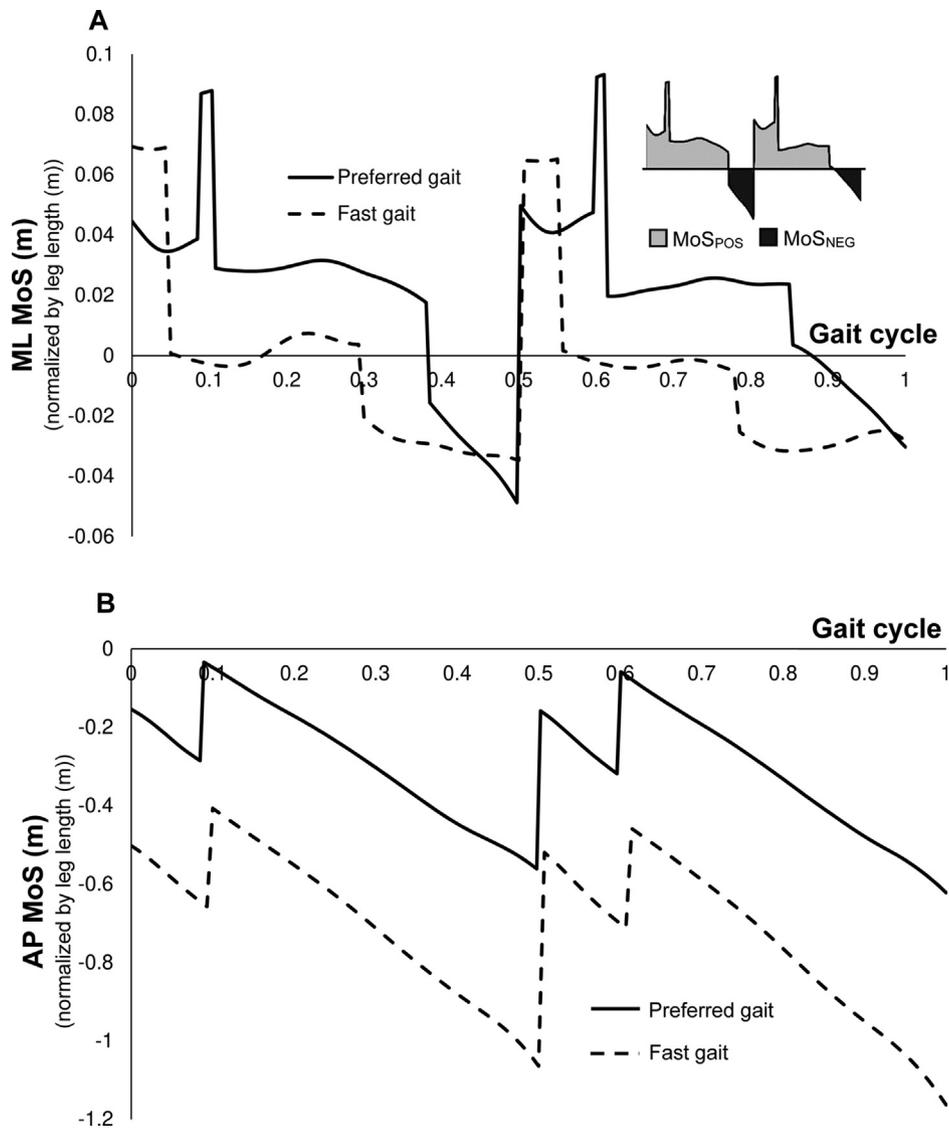
Fig. 6. A is an example of the preferred gait and a fast gait representing ML MoS, whereas B is an example of the preferred gait and fast gait representing AP MoS. The right HS is 0, and the left HS is approximately 0.5 in the gait cycle.

Table 1
Spatial-temporal gait parameters.

	Preferred gait	Fast gait
Walking speed (m/s)	1.25 (0.13)	2.11 (0.23)*
Cadence (steps/min)	114.0 (7.4)	149.7 (13.9)*
Step length (m)	0.657 (0.043)	0.843 (0.062)*
Step width (m)	0.067 (0.028)	0.083 (0.022)*

Values are means (SD).
* Significant differences between preferred gait and fast gait (p < 0.01).

Table 2
MoS parameters.

	Preferred gait	Fast gait
ML MoS$_{POS}$	0.051 (0.014)	0.027 (0.011)*
ML MoS$_{NEG}$	−0.0076 (0.0081)	−0.0257 (0.0214)*
ML MoS$_{mean}$	0.0219 (0.0104)	0.0007 (0.0149)*
AP MoS$_{mean}$	−0.346 (0.061)	−0.753 (0.120)*

Values are means (SD).
MoS parameters (m) are data normalized by the length of the lower limb (m) and have no units.
ML MoS$_{POS}$ and ML MoS$_{NEG}$ are time integrals (a gait cycle as 1.0) of ML MoS.
* Significant differences between preferred gait and fast gait (p < 0.01).

of walking speed (p < 0.05). No significant difference was found between the pre right HS and the pre left HS. The same results were obtained with AP MoS.

4. Discussion

A significant difference in walking speed between the two conditions of a preferred gait and a fast gait confirmed that participants walked at different speeds according to experimental directions. The cadence and step length also increased significantly at a fast gait, similarly to previous research involving healthy young adults (Sekiya et al., 1997). Although the step width increased significantly at a fast gait in the present study, no previous studies described the same result and observed clear differences in the step width (Table 1) (Sekiya et al., 1997; Murata et al., 2004).

As for MoS parameters, ML MoS$_{POS}$, ML MoS$_{NEG}$, and ML MoS$_{mean}$ were significantly less at a fast gait. Few reports in the
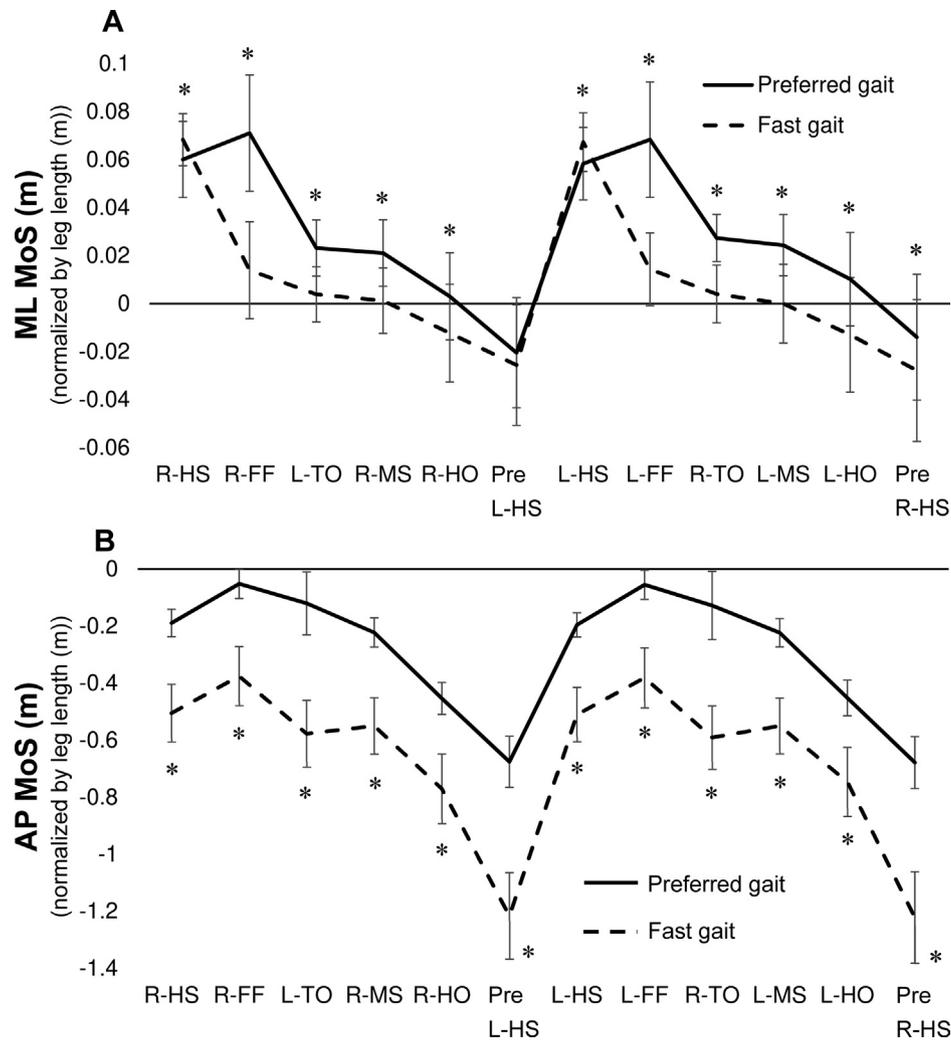
Fig. 7. Comparison of ML/AP MoS at 12 gait events and walking speed. R- represents right and L- represents left. *: Significant simple main effects by speed factors on gait event level (p < 0.001).

literature have described a study comparing ML MoS over a cycle, mainly because of the inherent computational complexity. Actually, in most studies where ML MoS is applied, the ML BoS boundary is defined as the lateral boundary of the feet, and values are evaluated only in the positive range (Curtze et al., 2011; McAndrew Young and Dingwell, 2012; He et al., 2018). Sivakumaran et al. (2018) discussed the importance of defining negative values considering medial markers for ML MoS. The reason is that the negative period of MoS represents an unstable state. It is necessary to change the BoS by a stepping strategy to recover stability (Hof et al., 2005; Bruijn et al., 2013). Therefore, ML MoS$_{POS}$ and ML MoS$_{NEG}$ were used to investigate the phase (and degree) of dynamic stability and instability, respectively. These values suggest that healthy young adults are walking with less stability and higher instability at a fast gait. ML MoS$_{mean}$ also probably became lower because the state of dynamic stability became lower at the fast gait. Although there are previous studies (e.g., Hof et al., 2007; McAndrew Young and Dingwell, 2012) investigating ML MoS$_{mean}$, it cannot be referred to as a value because the calculation method was different. In these previous studies, MoS was calculated as a positive value when XcoM was on the medial side of BoS, but in the present study it was interpreted as a negative value. Therefore, ML MoS$_{mean}$ became higher at a fast gait in the study of Hof et al. (2007), but it became smaller in the present study. AP

MoS$_{mean}$ was significantly less at a fast gait than at a preferred gait, which shows agreement with a report by Mademli and Arampatzis (2014). They defined the fraction of a fast gait to a preferred gait as a safety factor at AP MoS$_{mean}$ and demonstrated that the value was significantly lower for elderly people. In other words, it is difficult for elderly people to reduce AP MoS$_{mean}$ by increasing the walking speed from the state of high AP MoS$_{mean}$ at their preferred gait. Therefore, comparing subjects with AP MoS$_{mean}$ may be useful for investigating gait strategies, especially in terms of locomotion safety.

Comparison of ML MoS between gait events indicates significant interaction between speed factors and gait event factors and significant simple main effects, except for the pre left HS. MoS was high at the left and right HS at a fast gait, but the MoS was low with almost all gait events except for HS. In addition, ML MoS at pre-HS was significantly low at both preferred and fast gaits. The smaller positive values of ML MoS indicate that the subjects were in a more unstable "state". When the value turns negative, they enter a more unstable "state". Therefore, they may be walking with increased instability at a fast gait. The difference in MoS due to walking speed may be attributed to the ability of healthy young adults to maintain balance during walking. Sivakumaran et al. (2018) reported from their treadmill study that the minimum ML MoS in the first half of a swing phase (until the

opposite limb reaches MS) was significantly lower at a fast gait, which shows agreement with the result obtained in the period from FF to MS in the present study. Although some reports found that ML MoS becomes higher at a gait with a broad step width at HS (McAndrew Young and Dingwell, 2012), no report has made comparisons at a fast gait. Other reports presented comparisons of ML MoS at HS accompanying an increment in speed (from 1.2 m/s to 1.6 m/s), but there was no significant difference (Sivakumaran et al., 2018). In addition, in this result, although ML MoS at HS showed a significant difference in walking speed, the difference in mean values was smaller compared to other gait events. Therefore, HS may not be the best gait event to investigate differences in ML MoS with walking speed in healthy young adults.

Comparison of AP MoS between gait events also indicated significant interaction between speed factors and gait event factors and significant simple main effects in all gait events. Consequently, the MoS was low in fast gait through the gait cycle. Some reports found that AP MoS at HS and MS was significantly lower at a fast gait than at a preferred gait (Peebles et al., 2016), in agreement with the present study. Furthermore, AP MoS was significantly lower at a fast gait at the pre-right/left HS, when its value would become significantly lower. The minimum AP MoS was reported to decrease significantly with the increment in speed or step length (Sivakumaran et al., 2018), in agreement with the result of the present study. We consider that AP MoS decreased at pre-HS because of the greater speed and step length at a fast gait in the present result.

5. Conclusion

The discussion presented above suggests that the pre-HS is the most unstable moment in both ML/AP directions and a crucial moment in the control of gait stability. Therefore, this value at pre-HS appears to be one of the factors determining whether a fall will occur if heel strike is not successful (e.g., slip). Individuals who fear falling may have a strategy to prevent instability at pre-HS. Markedly low values of ML MoS_{POS}, ML MoS_{NEG}, and ML/AP MoS_{mean} at a fast gait suggest the possibility of applying these values as performance measures reflecting dynamic stability. The results explained above might be applicable as basic comparison data of dynamic stability of healthy young adults through a gait cycle.

This study was also limited by the fact that BoS is composed of heels and/or MTPs. Therefore, the transition period (e.g., transition from HS to FF) was not considered. Only one gait cycle was captured per trial by restriction of the volume of the experimental environment. Our future target will not be limited to healthy young adults: data of elderly people and patients with orthopedic disorders or neurological disorders will be compared. We will then investigate the gait strategy of individuals with a balance disorder and conduct a comparison with the conventional measures of dynamic stability.

Declaration of Competing Interest

None.

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