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Article

A Comparison of Dynamic Gait Stability between the Young and Elderly Female Populations Using the Zero-Moment Point Method

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Abstract: A compromised stability in the elderly population is considered a major factor for fall risk assessment. The dynamic stability of human gait with various mathematical metrics has been extensively studied to find a prediction index and fall prevention strategies that can be embedded in a wearable monitoring sensor. In this study, the zero-moment point method (ZMP) was utilized for analyzing the gait stability of young and elderly female populations. Participants in the young and elderly female groups with no musculoskeletal disorders and fall experience were asked to walk at a habitual speed on 10 m flat ground. Dynamic instability is defined by the percentage of the ZMP values that fall outside the base of support during one gait cycle. The ZMP trajectory between the left and right leg swing was not symmetrical considering flat-ground walking. Also, there was no statistical difference in the dynamic stability in the anterior–posterior direction (71.3 ± 7.9% for the young group and 73.6 ± 7.6% for the elderly group), but walking in the medial–lateral direction was more stable in the elderly group (53.9 ± 8.6%) than in the young group (44.1 ± 11.2%) because the habitual walking speed decreased in the elderly group.

Keywords: zero-moment point method; dynamic stability; gait analysis; age; biomechanical metrics

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1. Introduction

Falls are one of the main health problems in the elderly population because they cause traumatic injuries such as bone fractures [1]. Bone fractures in the elderly are associated with increased morbidity and mortality [2]. Since the fundamental prevention of falls is difficult for the elderly population, the prediction of falls with potential risk factors such as stability and sarcopenia has been intensively investigated [3]. In the elderly population, compromised stability caused by sarcopenia, neurological conditions, and inner ear problems is considered a major fall risk factor [4]. Quantifying the risk of falls with compromised stability assessment has been studied in order to design prevention strategies and provide an embedded algorithm for fall monitoring sensors [5–8]. Furthermore, in the rapidly developing field of wearable triboelectric sensors, an embedded assessment algorithm plays an essential role in sensing human motion and machine interfaces in robotics [9,10].

For a static stability assessment, the postural sway, which is the trajectory of a center of pressure (COP) or center of mass (COM) with respect to the base of support, is widely utilized [11]. For a dynamic stability assessment, the timed up-and-go test (TUG), the four-square step test (FSST), and the six-minute walking test are commonly used for evaluating a subject's dynamic performance [12]. These performance-oriented assessments are more used in clinical settings for fall risk analysis. In addition, dynamic stability has been investigated using various mathematical metrics, including the feasible stability region for biped, legged walking robots [3], the margin of stability (MOS) based on the extrapolated center of mass (XCOM) [13,14], the foot rotation indicator point [15], the step capturability analysis [16], and the maximal finite-time Lyapunov exponent [17].

Another mathematical metric for dynamic stability is the zero-moment point (ZMP) method, which was originally introduced for the dynamic control of legged robots, such as humanoid or quadrupedal robots [18]. A ZMP is defined as the point at which the dynamic reaction force at the contact of the foot with the ground does not produce any moment in the horizontal direction. The calculation of the ZMP also involves the forces generated by acceleration due to dynamic motion [18]. The stability analysis of human walking can be simplified with the ZMP method despite the complexity of the calculation, for which the acceleration of each body segment at every time point needs to be analyzed [18–23]. In the ZMP method, dynamic stability is guaranteed when the ZMP is within the base of support (BOS) in biped robots or legged robots, which mimic human-like walking [18]. Since the ZMP method includes acceleration values, the analysis is more sensitive than the other measures calculated using displacements and velocities. The ZMP method has been mostly applied for the analysis of biped robot walking. The study of Firmani and Park (2012) demonstrated the feasibility of using the ZMP method to assess human gait stability for the first time [20]. Many previous studies of dynamic stability involved young populations or using a treadmill system [14,17,21], which may limit the understanding of dynamic stability in the elderly population. Therefore, the purpose of this study was to demonstrate that the ZMP method can be utilized for analyzing the dynamic stability of walking on flat floors between the young and elderly populations for a better understanding of the elderly's gait biomechanics. The human gait data were analyzed using the COM, XCOM, and ZMP to compare the differences between these measures.

2. Materials and Methods

2.1. ZMP Analysis

The human gait can be analyzed by simplifying it into a motion involving seven segments (a 3D biped model comprising the upper body, two thighs, two shins, and two feet) [24] (Figure 1).

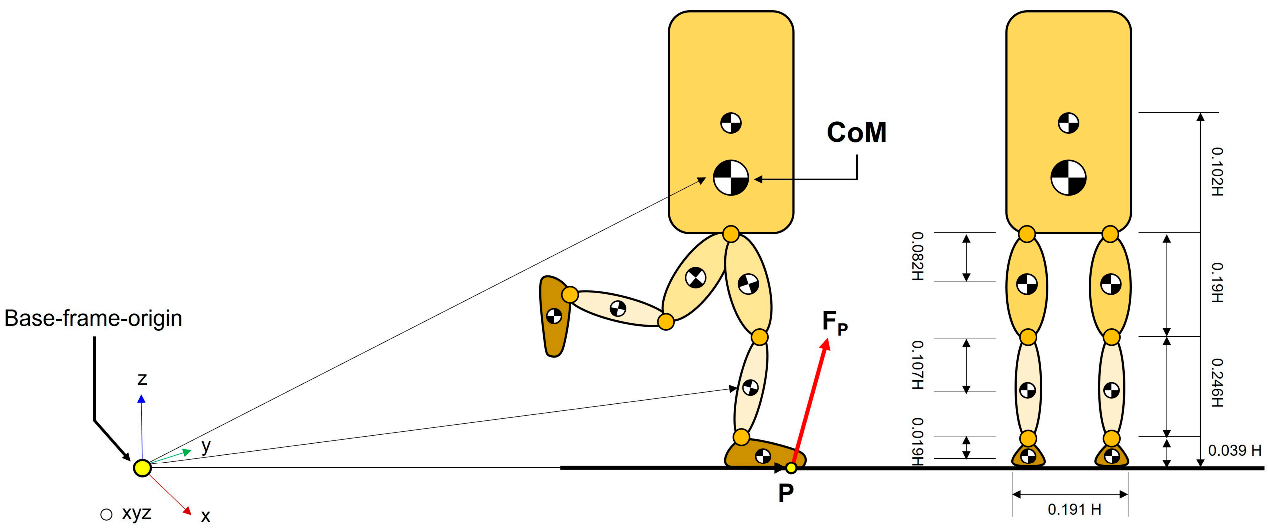

Figure 1. A conventional 3D biped model and anthropometric definition, where H is the height of the subject.

The COM and ZMP trajectory of the ideal normal gait is shown in Figure 2. During the double-limb support period, the COM is located at the midpoint between the two supporting feet and moves to the side where the feet are in contact with the ground during the single-limb support phase [25]. For the coordinates of the COM and the body mass values of each segment, we used the anthropometric data defined in the study of Winter 1984 [26] (Figure 1). By inputting the subject's height and weight and applying the proposed coefficients, the weight of each human body segment and the position of the COM can be calculated.

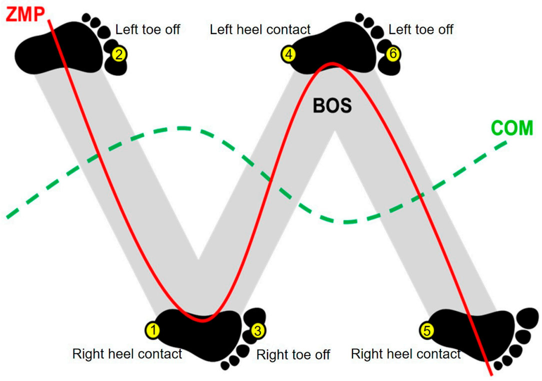

Figure 2. Illustration of trajectories of COM and ZMP in ideal walking.

Then, the BOS was measured by calculating the maximum and minimum points based on the sole markers of the subject, which were attached according to the Helen Hayes marker set. The position of the center of gravity and the ZMP for each subject were calculated by using a simplified trunk–leg (7-link) model of the human body based on the anthropometric data (Figure 1). In general, the ZMP at which the dynamic equilibrium state can be assessed, i.e., the point at which the sum of the forces and moments of all joints becomes 0, can be expressed using Equations (1) and (2) (Table 1).

$$x_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i \ddot{x}_i z_i - \sum_{i=1}^{n} I_{iy}\,\ddot{\theta}_{iy}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \quad (1)$$

$$y_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i \ddot{y}_i z_i - \sum_{i=1}^{n} I_{ix}\ddot{\theta}_{ix}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \quad (2)$$

Table 1. Symbols for ZMP equations.

Symbol	Name	
m_i	Body segment's mass	
g	gravity	9.8 m/s^2
x_i y_i z_i	Body segment's position	m
$\ddot{x}_i$, $\ddot{y}_i$, $\ddot{z}_i$	Body segment's acceleration	m/s^2
I_{ix} I_{iy}	Body segment's moment of inertia	m r^2
$\ddot{\theta}_{ix}$ $\ddot{\theta}_{iy}$	Body segment's angular acceleration	rad/s^2

In addition, the XCOM in the AP and ML directions were calculated using Equations (3)–(5) as follows:

$$X_{COM} = X + \frac{V_{COM}}{\omega_0} \quad (3)$$

$$V_{COM} = Speed\ of\ COM \quad (4)$$

$$\omega_0 = \sqrt{\frac{g}{l}} \quad (5)$$

where g is the gravitational acceleration (9.81 m/s^2), and l is the equivalent pendulum length, i.e., the mean distance from the lateral ankle marker to the COM at heel strike.

2.2. Experiments

Dynamic gait experiments were performed among young and elderly female groups. In the young group (denoted as Y), 18 healthy subjects with a mean age of 22.8 ± 1.5 years, a mean body height of 163.6 ± 3.6 cm, and a mean body weight of 58.3 ± 5.9 kg were recruited. In the elderly group (denoted as E), 18 healthy subjects with a mean age of 71.7 ± 4.0 years, a mean body height of 154.6 ± 4.6 cm, and a mean body weight of 59.5 ± 8.5 kg were recruited. All subjects claimed to have no musculoskeletal disease. Prior to the experiments, all participants provided informed consent, and the methods were approved by the Korea Institutional Review Board (P01-202109-11-005). Each participant was monitored using a Helen Hayes full-body marker set. Each participant, wearing the same running shoes in their own size (Prospecs, LS Networks, Seoul, Republic of Korea), was asked to walk at a habitual speed on a 10 m flat surface. During walking, a three-dimensional motion capture system (Motion Analysis, Rohnert Park, CA, USA) with 8 infrared cameras was used to record marker trajectories at a sampling rate of 100 Hz (Figure 3). The data of markers were filtered by using a Butterworth low-pass filter with a cut-off frequency of 6 Hz.

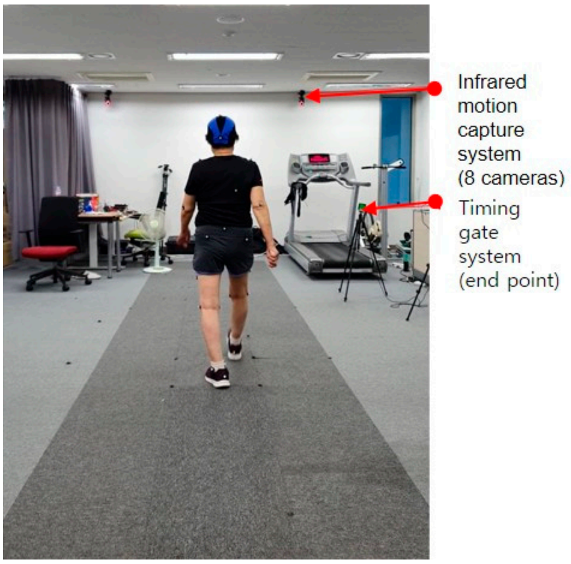

Figure 3. An experimental setup for gait tests.

2.3. Data Analysis

For the comparison of variables within each group and between groups, the COM, XCOM, ZMP, and minimum and maximum BOS were normalized by the BOS range, which is from the minimum to maximum BOS, and presented considering a single normalized gait cycle. Dynamic instability is defined by the percentage of ZMP values that fall outside the base of support during one gait cycle.

A comparison of the ZMP between young and elderly groups was performed using an independent t-test. The level of significance for all tests was set at $p = 0.05$. The results are presented as means ± standard deviation in the text and means ± standard error of the mean in the figures. All normalization processes and the statistical significance analysis of the ZMP between the young and elderly groups were performed using MATLAB version R2023a (MathWorks, Natick, MA, USA).

3. Results

The average habitual walking speed of the young group and the elderly group was 1.34 ± 0.11 m/s and 1.18 ± 0.09 m/s, respectively. The stance and swing phases for the young group were 56.4 ± 1.4% and 43.6 ± 1.4%, respectively. The stance and swing phases for the elderly group were 57.9 ± 1.4% and 42.1 ± 1.4%, respectively. The period of double-limb support was 13.0 ± 2.4% and 16.1 ± 2.7% for the young and the elderly groups, respectively. These results show that, compared with the young group, the support period for both feet in the elderly group increased in order to increase the stability of walking at a slower walking speed.

The first double-limb support of the right heel contact was 6.3 ± 1.7% and 8.1 ± 1.7% for the young and elderly groups, respectively. The second double-limb support of the left heel contact was 6.7 ± 1.2% and 8.0 ± 1.4% for the young and elderly groups, respectively (Table 2).

Table 2. Comparison of the results between the young and elderly groups (means ± standard deviation [%]).

	Dynamic Stability in A-P	Dynamic Stability in M-L	Stance Phase	Swing Phase	First Double Limb	Second Double Limb
Young	71.3 ± 7.9	44.1 ± 11.2	56.4 ± 1.4	43.6 ± 1.4	6.3 ± 1.7	6.7 ± 1.2
Elderly	73.6 ± 7.6	53.9 ± 8.6	57.9 ± 1.4	42.1 ± 1.4	8.1 ± 1.7	8.0 ± 1.4

When analyzing walking in the young group, we found that the ZMPs in the anterior–posterior (A-P) direction were dynamically stable on the double-limb supports, and an average of 71.3 ± 7.9% of the ZMP positions were located within the BOS during the gait cycle (Figure 4A). The ZMPs in the medial–lateral direction were dynamically stable on the first double-limb supports but not on the rest of the gait cycle. For a single gait cycle, an average of 44.1 ± 11.2% of the ZMP positions were located within the BOS (Table 2, Figures 5A and 6B).

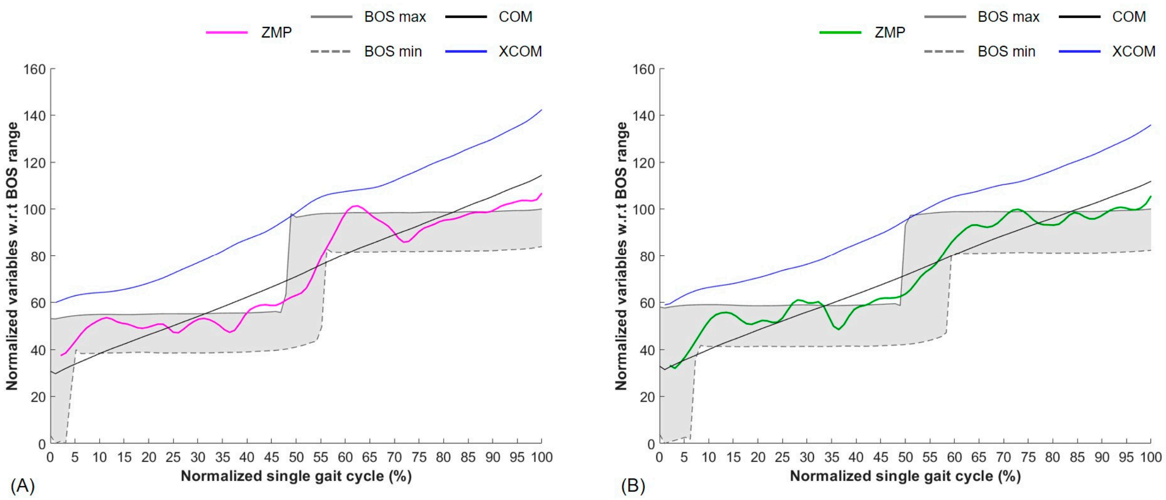

Figure 4. Examples of COM, XCOM, and ZMP trajectories during a single gait cycle in the young (**A**) and elderly (**B**) groups in the anterior–posterior direction. BOS max: maximum BOS trajectory, BOS min: minimum BOS trajectory. The shaded area shows the trajectory of the BOS range.

The gait analysis results in the elderly group revealed that the ZMPs in the anterior–posterior direction were dynamically stable on the double-limb supports, and an average of 73.6 ± 7.6% of the ZMP positions were located within the BOS during the gait cycle (Table 2, Figures 4B and 6A). The ZMPs in the medial–lateral direction were dynamically stable on the first double-limb supports but not on the rest of the gait cycle. For a single gait cycle, an average of 53.9 ± 8.6% of the ZMP positions were located within the BOS (Table 2, Figures 5B and 6B).

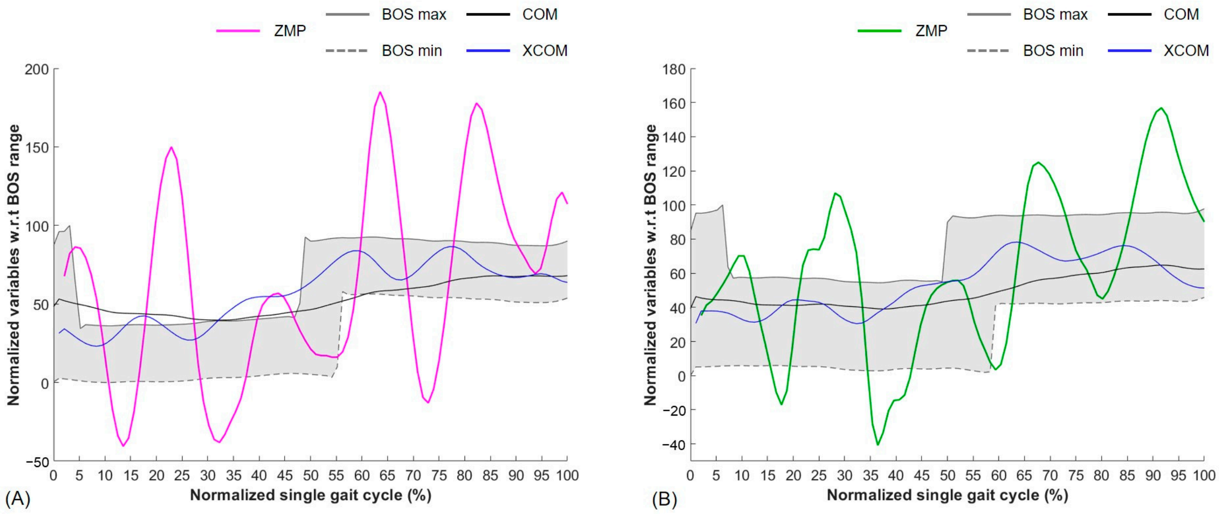

Figure 5. Examples of COM, XCOM, and ZMP trajectories during a single gait cycle in the young (**A**) and elderly (**B**) groups in the medial–lateral direction. BOS max: maximum BOS trajectory, BOS min: minimum BOS trajectory. The shaded area shows the trajectory of the BOS range.

In the anterior–posterior direction, the walking gait in the elderly group was similar to that in the young group ($p = 0.87$, Figure 6A). In the medial–lateral direction, the dynamic stability, i.e., the percentage of the ZMP falling within the BOS, in the EG was similar to that in the YG (Figure 6B). In addition, the average ZMP peak trajectory in the ML direction of the EG tended to be slightly delayed compared to that of the YG (Figure 6B).

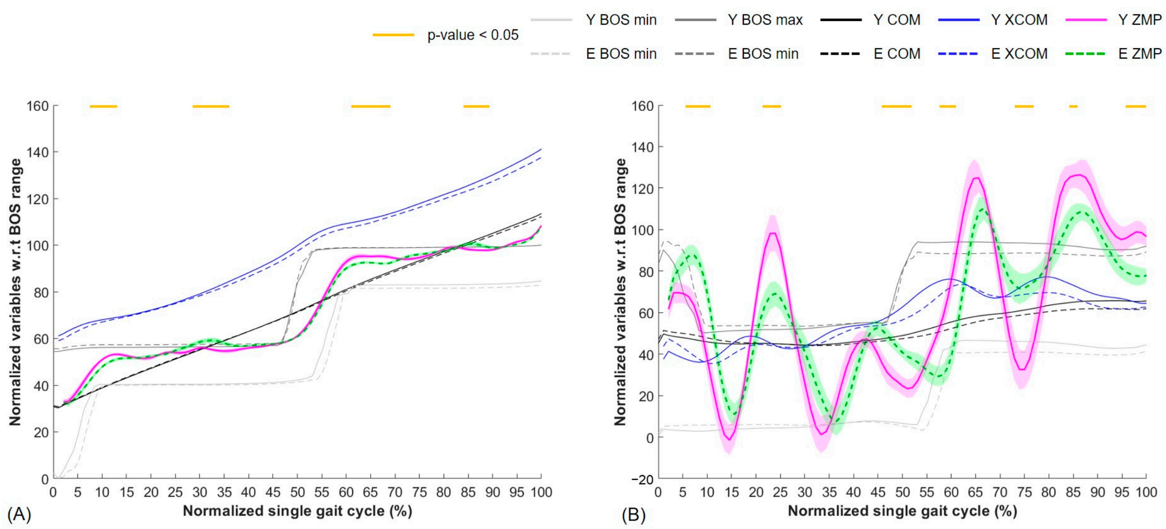

Figure 6. Comparison of average COM, XCOM, and ZMP trajectory during a single gait cycle between the young and elderly groups. (**A**) in the anterior–posterior direction, (**B**) in the medial–lateral direction. Y: the young group, E: the elderly group. BOS max: maximum BOS trajectory, BOS min: minimum BOS trajectory. The shaded area shows the trajectory of the BOS range.

4. Discussion

The dynamic walking stability of the young and elderly groups was quantitatively analyzed using the ZMP method and compared with the COM and XCOM measures. In agreement with previous studies [27–30], it was found that there was a decrease in walking speed, an increase in the double-limb support time, and a shorter step length for the elderly population in this study. There was no statistical difference in the dynamic stability in the anterior–posterior direction (71.3 ± 7.9% for the young group and 73.6 ± 7.6% for the elderly group), but the gait in the elderly group in the medial–lateral direction was more stable (53.9 ± 8.6%) than in the young group (44.3 ± 11.0%) because the habitual walking speed in the elderly group decreased. In the anterior–posterior direction, the ZMP trajectories for both the young and elderly groups were within the BOS limits, indicating that a stable state was maintained in both groups (Figure 4). The first double-limb support of the right heel contact was 6.3 ± 1.7% and 8.1 ± 1.7% for the young and elderly groups, respectively. The second double-limb support of the left heel contact was 6.7 ± 1.2% and 8.0 ± 1.4% for the young and elderly groups, respectively. These results indicate a longer double-limb support time in the elderly compared with the young group. Also, the peak amplitude of the ZMP trajectories in the medial–lateral direction in the elderly group shifted backward compared with the young group, which is believed to be caused by the difference in the reaction speed of the movement of the lower extremity segments (Figure 6B). The ZMP amplitude/sway directly depends on the walking speed. Therefore, the slower habitual walking speed in the elderly group led to higher dynamic stability in the medial–lateral direction compared with the young group. Moreover, since there was adequate dynamic stability in the anterior–posterior direction for the young group considering their habitual walking speed, the slower walking speed in the elderly group compared to the young group did not significantly contribute to an increase in the dynamic stability.

In the young group, walking began from the point of contact with the heel of the right leg, and at this time, the BOS moved to the top of the right leg based on the lowest end of the left leg (Figure 5A). The position of the COM was at the central point of the BOS and then progressively advanced to the next left-heel contact. As the gait progressed, the COM deviated from the BOS in the pre-swing section of the left leg and right leg, resulting from the propulsion generated during the gait cycle. Considering the change in the ZMP of the anterior–posterior direction, deceleration due to heel contact at the start of the double-limb section and acceleration due to propulsion at the end of the double-limb section repeatedly occurred.

Compared with the previous ZMP studies [21], the patterns of the ZMP trajectories in the medial–lateral direction in this study were very non-symmetrical (Figures 5 and 6B). The trajectories of the COM and ZMP in the medial–lateral direction in the young group gradually moved toward the left (Figures 5 and 6B). In an ideal gait, the left–right symmetry should be the same, but in an actual gait, left–right directionality occurs, which is due to the asymmetry of the pelvis or the difference in left–right symmetry. Also, this difference is due to the difference in the experimental design of walking floor conditions. In the study of Firmani and Park 2013 [20], subjects walked on a two-belt treadmill at a given walking speed, whereas the subjects in this study walked on flat ground at habitual speed. Therefore, it could be anticipated that the subjects walking on the two-belt treadmill were forced to walk with the same speed of both left and right leg swing, whereas those walking on the flat ground walked more naturally.

This is a novel study that involves a comparison of gait stability between the young and elderly populations in their habitual walking speed using the ZMP method. Most previous studies for understanding gait stability in the elderly focused on gait characteristics, such as walking speed, stride length, and the time for double-limb support [31]. In this study, the dynamic stability of habitual walking was assessed to investigate the gait of the elderly compared to the young. Since the habitual walking speed of the elderly is generally slower than the young, the dynamic stability of the elderly who have no fall experience and lead an active lifestyle is more stable than the young. The ZMP method is sensitive to gait speed due to the formulation of its equation, and this sensitivity is considered a contributing factor to gait instability. Additionally, the previous study by Firmani and Park (2012) was conducted in a treadmill environment at a fixed speed, which limits the ability to capture the natural variability and adaptability of human gait [20]. To address these limitations, this study was designed to assess gait stability in a habitual walking setting on a flat surface. Our findings suggest that the gait biomechanics and ZMP analysis of elderly individuals may differ from those of younger individuals when both groups walk at the same speed.

This study was conducted with eighteen subjects for each of the two different age groups. In the elderly group, the average age was 71.7 ± 4.0 years and most of the subjects led an active lifestyle, for instance, working part-time for the community. A recent study involving elderly age groups over and under 74 years old revealed that they have substantially different gait biomechanics [31]. The limited number of subjects and relatively young age and active lifestyle in the elderly group did not allow us to reach a general conclusion. In order to have a better understanding of dynamic stability in the elderly, further studies using the ZMP method should include subjects with fall experience who may have different walking characteristics and various walking speeds in experimental conditions, which provide an assessment of response characteristics. In addition, gait experiments with different ground slop conditions or with obstacles can help to investigate dynamic instability and walking characteristics that reflect the everyday life of the elderly.

The ZMP method can be used as a metric for analyzing the dynamic stability of human walking, which can be embedded in a wearable monitoring sensor. Compared to the XCOM trajectory based on the velocity of the COM, the ZMP trajectory is more sensitive (Figures 4–6), because it is calculated with acceleration values. In a future study, we will investigate how artificial intelligence and deep learning algorithms with ZMP data alone or combined with other measurement data can be used to classify the elderly with fall experience and young populations.

5. Conclusions

In this study, the ZMP method was utilized for analyzing the dynamic stability of habitual walking among the young and elderly populations. There was no statistical difference in the dynamic stability in the anterior–posterior direction (71.3 ± 7.9% for the young group and 73.6 ± 7.6% for the elderly group), but the habitual walking in the elderly group in the medial–lateral direction was more stable (53.9 ± 8.6%) than in the young group (44.1 ± 11.2%) because the habitual walking speed decreased: The average habitual walking speed of the young group and the elderly group was 1.34 ± 0.11 m/s and 1.18 ± 0.09 m/s, respectively. For a more in-depth analysis of the gait stability or fall risk prediction of the elderly using the ZMP method, various walking speeds or obstacle conditions should be considered to take into account the dynamic interactions in the elderly.

Author Contributions: S.K.H., J.-S.H., J.-C.R., K.K.L. and S.-J.K. designed the project and planned the experiments. S.K.H., Y.Y. and S.-J.K. conducted experiments. S.K.H., S.-J.K. and J.-B.K. contributed to the numerical and statistical analysis. All authors participated in writing and reviewing the manuscript. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest: The authors declare no conflicts of interest.

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