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Gait Analysis of Elderly and Young People Based on Joint Angles and Positions

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Abstract: For the elderly, the motor function of walking is significant for the maintenance and improvement of their quality of life (QOL). Walking patterns have been postulated to be associated with a decline in walking ability. The objective of this study was to develop a wearable sensor that can capture changes in walking ability in daily life. To this end, motion capture was employed to measure the lower limb joint angles and the trajectories of the lower limbs and knees for each subject while walking at a normal walking speed and to compare the results between elderly and young patients. The differences in walking patterns between the elderly and young patients were analyzed in terms of elevation angles, and an index was calculated to capture changes during walking based on elevation angles and trajectories.

Keywords: elevation angle; gait; planar covariation law; elderly; posture

1. Introduction

The population of elderly aged 65 and over in Japan has reached 3,627,000 (as of 1 October 2023), accounting for 29.1% of the total population, and the country has become a super-aged society [1]. According to an estimate published by the Cabinet Office, by 2040, 35% of the total population will be aged 65 years or older. Aging can contribute to a variety of problems, such as a decline in physical fitness due to reduced muscle strength and endurance and susceptibility to epidemics due to a weakened immune system. More than 6.3 million people, accounting for approximately 18% of the elderly population, are in need of care [2]. One of the causes of the need for nursing care is a decline in walking ability. The ability to walk changes with age and declines markedly after the age of 60–70 years [3]. With regard to the elderly, the ability to walk is considered to be the minimum motor ability required for independence and maintaining a good quality of life [4].

Therefore, we investigated the characteristics of gait posture that capture changes in daily walking ability. In particular, Japanese people are said to have a high percentage of bowlegged lower limb alignment [5], and it has been reported that the percentage of bowleggedness increases with age and is more common in women [6]. This is one of the causes of knee osteoarthritis [7,8]. In the past, we examined how walking posture changes with lower limb alignment, particularly focusing on the hip, knee, and ankle joints during gait and the differences in gait surface methods in young people [9]. In this study, we investigated whether gait posture and trajectory data can be used to detect declines in walking ability in elderly people and young adults with normal walking ability by focusing on and comparing the planar covariance law (PCL) described below in Section 3.2. It is known that the PCL simplifies the cooperative control of posture and movement [10–12]; this was discovered when researchers examined the conditions to which humans should adapt in order to acquire gait, including the evolutionary process [13]. It has also been clarified that the PCL is not affected by declines in walking speed and/or stride length due to declines in muscle strength [14,15] or deterioration of the nervous and sensory

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systems due to aging, nor is it affected by aging itself [16]. Although several studies have established PCL values under constant speed conditions using a treadmill and with highly correlated joint angles, few have examined PCL and gait trajectory variations between young and old people at their normal walking speeds in their daily living environments.

In this study, healthy young and elderly people without walking problems were compared using the 25-question Geriatric Locomotive Function Scale (described below in Section 2.1), and we investigated walking characteristics that could serve as new indicators for maintaining and improving walking ability.

2. Materials and Methods

2.1. Participants

The participants were five elderly people with normal gait (minimum age 65; age 76.4 ± 2.58 years, height 156 ± 7.58 cm, and weight 65.6 ± 6.72 kg (mean ± SD); labeled No. 1, 2, 3, 4, and 5) and five young people (age 22.4 ± 1.20 years, height 173 ± 6.47 cm, and weight 62.2 ± 6.92 kg (mean ± SD); labeled No. 6, 7, 8, 9, and 10). The participant information is listed in Table 1. Individuals who were unable to ambulate independently were excluded from the study.

Table 1. Participants information.

	Healthy Elderly People	Healthy Young People
Age (years)	76.4 ± 2.58	22.4 ± 1.20
Height (cm)	156 ± 7.58	173 ± 6.47
Weight (kg)	65.6 ± 6.72	62.2 ± 6.92

The participants were administered the 25-question Geriatric Locomotive Function Scale (GLFS-25) [17,18], a subjective evaluation designed to assess their physical and living conditions and to identify any potential inconveniences. The GLFS-25 is a self-administered questionnaire comprising 25 questions designed to examine living conditions and motor function. The questions are graded on a 5-point scale with choices from 0 to 4. A lower total score indicates better gait function. A total score of less than 7 points indicates locomotive syndrome stage (LS stage) 0 and no problems; between 7 and 16 points indicates LS stage 1, where gait function has started to decline; between 16 and 24 points indicates a level of advanced gait dysfunction; 24 points or more indicates a level at which gait function has declined to the point where social participation is impaired. Table 2 shows the results of the GLFS-25 test. Among the elderly participants, one exhibited a score of 0, one exhibited a score of 3, two exhibited a score of 7, and one exhibited a score of 8. Accordingly, two individuals exhibited LS stage 0, and three individuals exhibited LS stage 1. Among the younger subjects, one exhibited a score of 0, one exhibited a score of 1, one exhibited a score of 2, and two exhibited a score of 4; all of them exhibited LS stage 0. The elderly individuals with scores of 7 or 8 were those who selected Level 1 for items related to participation in social activities and concerns about future walking, resulting in an additional 3 points. They were at the borderline between LS stages 0 and 1 and had the same level of elevated activity range and gait function as the other older adults, and they engaged in walking and other activities without problems. Therefore, they were classified as healthy elderly. The participant information is listed in Table 1. Participants who were unable to ambulate independently were excluded from the study.

The experiment followed Kwansei Gakuin University's regulations on ethics for the protection of human patients in medical research and was approved by the campus committee. Informed consent was obtained from all participants. The study protocol conformed to the principles of the Declaration of Helsinki.

Table 2. Scores for the 25-question Geriatric Locomotive Function Scale (GLFS-25).

	Healthy Elderly People					Healthy Young People				
Subject	**No.1**	**No.2**	**No.3**	**No.4**	**No.5**	**No.6**	**No.7**	**No.8**	**No.9**	**No.10**
Score	3	0	7	7	8	4	1	4	2	0
LS stage	0	0	1	1	1	0	0	0	0	0

2.2. Experimental Method

In this experiment, patients were asked to walk along an approximately 5 m path. Placing an embedded force plate on the floor created a step corresponding to the thickness of the force plate, which disrupted the participants' gait. Therefore, the experiment was conducted by installing a 40 mm thick wooden board to eliminate the step. The length of the walking path, including the floor reaction force meter, was determined to be long enough to ensure three gait cycles, taking into account variations in stride length and gait cycle. The total length of the auxiliary track was approximately 10 m length. The video images confirmed that there was no unnaturalness in the walking motion before and after overcoming the steps, and that one foot was placed on the force plate for the last gait cycle. After the participants practiced walking, measurements were taken using the force plate and walking posture at least three times per person, and one measurement was extracted. Walking speeds were calculated based on each subject's natural gait. A gait cycle was defined as the time from the second landing of the left heel to the regrounding of the left heel on the walking path based on camera images. The stance phase was defined as the period from heel contact to toe-off and accounted for approximately 60% of the gait cycle. The swing phase was defined as the period from toe-off of the left leg to re-entry of the left heel. To analyze motion during walking, four CCD cameras (Library Co., Ltd., Tokyo, Japan, Himawari GE60) captured images, and a synchronization unit (Library Co., Ltd., Tokyo, Japan; GE-SPU4/B) and a hub (Corega Inc., Yokohama, Japan; CG-SW05GTPLX) connected each camera to a LAN port on a PC. Motion analysis was conducted using a three-dimensional motion analyzer (Library Co., Ltd., Tokyo, Japan; Capture EX). The sampling rate was 50 Hz, and 50 images per second were acquired using the CCD cameras. Position coordinates were obtained using 3D video measurement software (Library Co., Ltd., Tokyo, Japan; Move-tr/3D Ver. 8.1). Figure 1 shows the experimental environment. The marker positions were set at four characteristic points (LASI, LKNE, LANK, and LTOE) on three body segments of the lower limb to obtain the elevation angle.

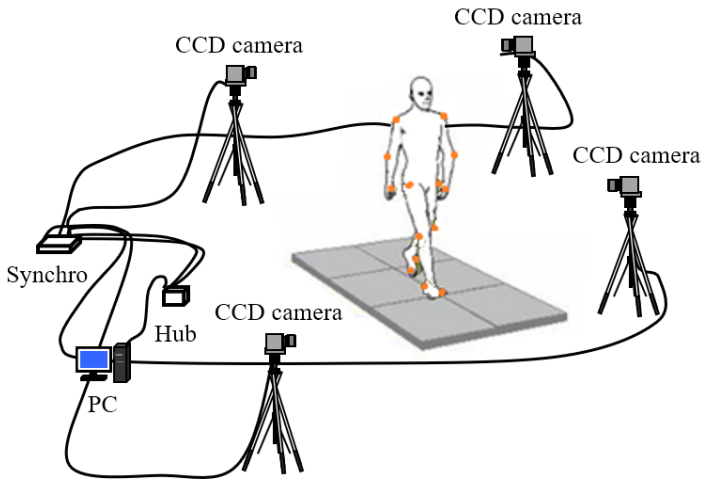

Figure 1. Experimental setup. Overview of the experiment using the motion capture system. The orange dots indicate the position of the motion capture markers.

3. Gait Analysis Using Elevation Angle

Three gait cycles were extracted from one of the three trials, and the average value was determined. One gait cycle was defined as the time [%] from heel contact to the next heel contact and was expressed as 100%. A *t*-test was used to determine the statistical significance.

3.1. Definition of Elevation Angle

The elevation angles (θ_{thigh}, θ_{shank}, and θ_{foot}) were defined as the angles between the three body segments of the human lower limb and the vertical direction. Figure 2 depicts the three lower-limb body segments and the upper body (HAT: head and torso), as well as the elevation angles between the body segments of the thigh, lower leg (shank), and foot (foot) and the vertical direction. For θ_{thigh}, θ_{shank}, and θ_{foot}, the coordinate axes of the vertical and horizontal absolute coordinate systems were employed to define the four coordinate positions of the characteristic points of the three lower-limb body segments (LASI, LKNE, LANK, and LTOE). The elevation angles for each participant were calculated from the inner product of each body segment and the vertical vector.

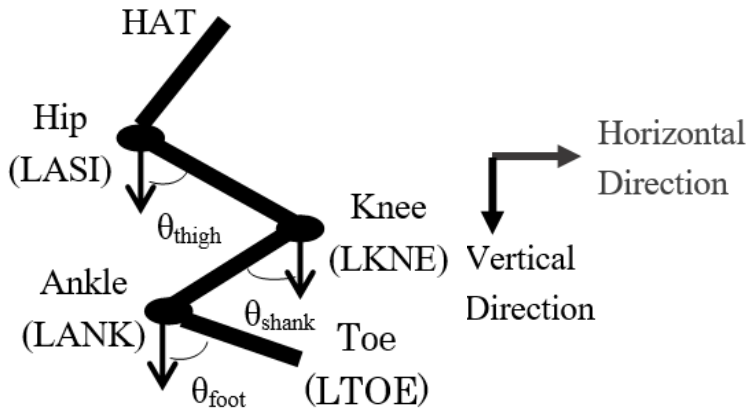

Figure 2. Elevation angle. The terms and positions related to the elevation angle are shown.

3.2. PCL of Elevation Angle

When the time series data of the angles (θ_{thigh}, θ_{shank}, and θ_{foot}) defined in Section 3.1 are plotted in three dimensions in one walking cycle, they appear in the same plane; this is called the plane law [13]. An approximate plane was generated from the measured data using principal component analysis [12]. The plane law implies that the three body segments of the lower limb do not move independently but are controlled by two degrees of freedom. The PCL observed in healthy elderly individuals is known to be as valid as the PCL in young people when walking based on the results of walking experiments at a constant speed on a treadmill [19,20]. However, in this study, the walking speed of the elderly was measured at a natural walking speed without the use of a treadmill and was compared with that of the PCL.

Figure 3a shows the elevation angles of one of the younger patients in this experiment and the characteristics of their gait. The approximate plane is depicted as a grid. The rings in the figure indicate the elevation angles, and the fluctuations in the elevation angles indicate the timing of left heel contact and left toe-off. The trajectory of the elevation angle is counterclockwise from heel contact to toe-off. Figure 3b shows a stick diagram in which one walking period corresponding to the elevation angle graph is set to 100%.

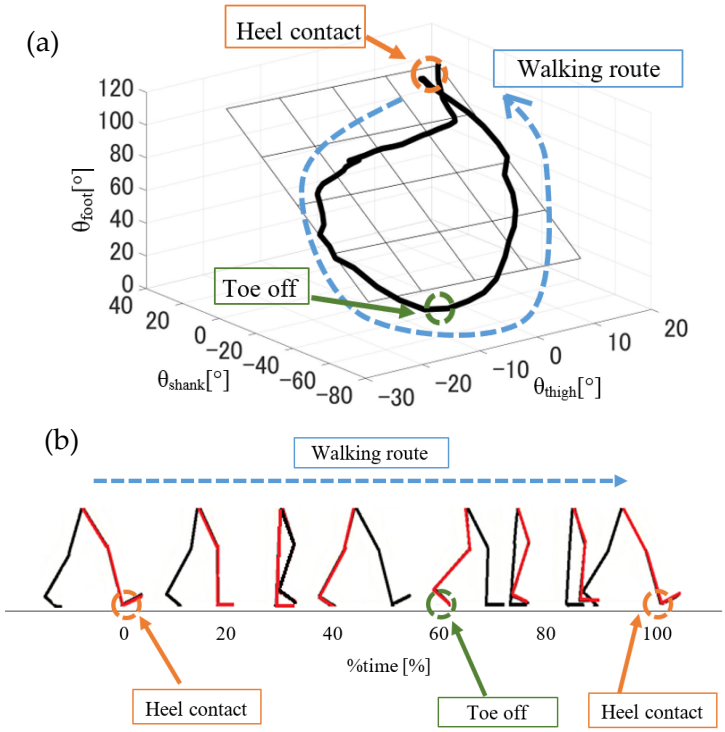

Figure 3. Relationship between PCL and one cycle of walking. (**a**) Example of PCL for elevation angle and stick figure for one walking cycle. (**b**) Time [%] is expressed in 100% based on one cycle of walking from heel contact to the next heel contact.

4. Results

4.1. Comparison of PCLs between Elderly and Young People

We used 3D plots to confirm how the elevation angles differed between elderly and young people. Figure 4 shows three-dimensional plots of the average elevation angles divided by age group for one walking cycle from left heel touch to left heel re-grounding. Elevation angles for the elderly patients are shown in blue, and those for the young patients are shown in red. The mean values were averaged for the elderly and young groups by applying a polynomial approximation to each participant's elevation angles, setting the gait cycle to 100%, and normalizing the gait cycle time. A grid was added to the approximate planes to show the differences. The size of the circle indicates the vertical movement of each participant.

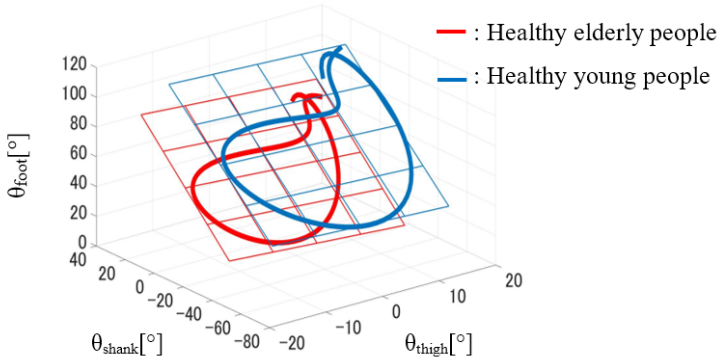

Figure 4. Comparison of PCLs between the elderly and young people.

Figure 4 shows that the ranges of motion of the elevation angles were smaller for the older patient, as in the conventional treadmill study. Aging has been reported to have no effect on limb coordination [21], and we confirmed that the PCL was established in both

young and elderly subjects. In addition, the closed circles for the three elevation angles were smaller for the elderly patients. This suggests that elderly people have a decreased range of motion of the lower limbs during walking rather than variations in elevation angles as a result of changes in walking posture (e.g., hunchback).

Approximate planes were calculated from the obtained elevation angles, and the cumulative contribution rates shown in Table 3 were used to investigate whether the plane law holds after aging. The cumulative contribution rates were calculated as the sum of the contribution rates of the first and second principal components using the statistical processing software SPSS (IBM Japan, Ltd., Tokyo, Japan; IBM SPSS Statics ver. 24). Borghese N.A. et al. [12] reported cumulative contribution rates of 99% or more for all subjects (21–40 years). In their results, there was no significant difference between the elderly group and the young group. In addition, a *t*-test was performed between the elderly group and the young group, but there was no significant difference in the cumulative contribution rate.

Table 3. Cumulative contribution rates [%].

Healthy elderly people						
No.1	No.2	No.3	No.4	No.5	Mean	SD
99.31	99.41	98.65	99.42	99.27	99.21	0.29
Healthy young people						
No.6	No.7	No.8	No.9	No.10	Mean	SD
98.22	99.42	99.14	99.22	98.65	98.93	0.44

4.2. Changes in Elevation Angles θ_{thigh}, θ_{shank}, and θ_{foot} during One Gait Cycle

To examine the differences in elevation angles between the elderly and young, the changes in θ_{thigh}, θ_{shank}, and θ_{foot} within one walking cycle were examined. The changes in the angles are shown in Figure 5. For θ_{thigh}, the angles of the elderly participants tended to be smaller than those of the younger participants, indicating that thigh flexion/extension was decreased in the elderly. For θ_{shank}, thigh and lower leg flexion tended to be smaller for the elderly population from 60% to 70% of the way through the gait cycle. For θ_{foot}, the angles of the elderly patients were lower than those of the young patients from 0 to 50% and from 80% to 100% of the gait cycle, and it was confirmed that the flexion and dorsiflexion from the heel to the toe were decreased.

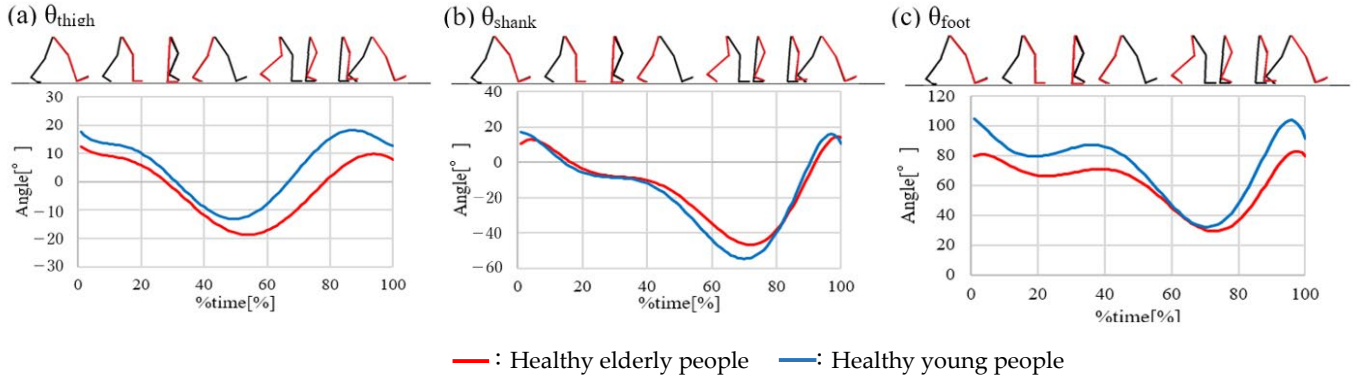

Figure 5. Average joint angles of θ_{thigh}, θ_{shank}, and θ_{foot}.

Figure 6 shows the differences between the maximum and minimum values of θ_{thigh}, θ_{shank}, and θ_{foot} from Figure 5. The mean values of θ_{thigh}, θ_{shank}, and θ_{foot} for the elderly and younger groups are shown, and the standard deviations were calculated for the mean values. This indicates the amount of angular change, which is the difference between flexion and extension for θthigh and θ_{shank} and between plantar flexion and dorsiflexion

for θ_{foot}. For all θ values, the elderly tended to show smaller angular changes in flexion and extension and in plantar flexion and dorsiflexion than the younger patients. In addition, *t*-tests showed significant differences for θ_{shank} and θ_{foot} between the elderly and young groups ($p < 0.05$).

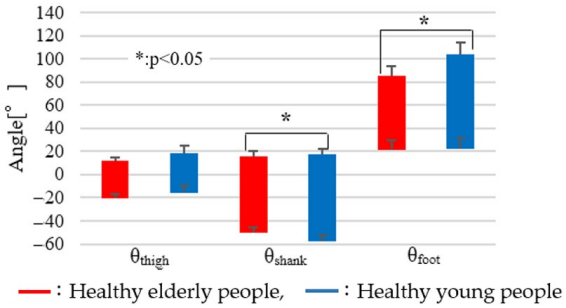

Figure 6. Average joint angles of θ_{thigh}, θ_{shank}, and θ_{foot}.

4.3. Lower Limb Trajectory

Figure 7 shows a stick figure of the movement of the lower limb during one gait cycle. The trajectories are shown as LASI, LKNE, LANK, and LTOE, with x in the left–right direction and z in the vertical direction in the sagittal plane. Stick figures were drawn such that the maximum swing in the x-direction and maximum kick-out in the x-direction were the maximum and minimum, respectively, during walking. Elderly people are shown in red and young people are shown in blue.

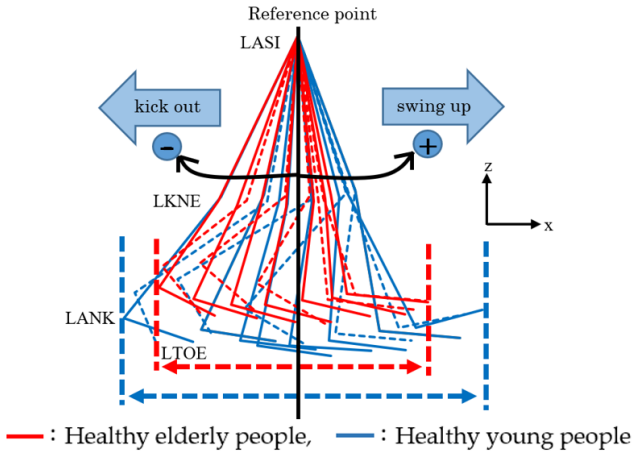

Figure 7. Stick figures of gait motion.

Comparing the trajectories of the lower limbs of elderly and young people within one walking cycle in Figure 7, there is a clear difference in the x-directional sagittal oscillation of the lower limbs (in walking, the x-directional oscillation is forward/backward). Figure 8 shows the mean values of the x-directional sway of elderly and young people. Figure 8 shows the mean values of the amplitude in the x direction for the elderly and younger groups. The results of Section 4.2 indicate that the elderly people showed a smaller difference in flexion and extension than the younger people and that there was a significant angular difference in the flexion and extension of the θ_{shank} and θ_{foot}, which may explain the difference in the x-directional sway (or front–back sway in walking) in Figure 7.

In addition, Figure 7 shows that the LTOE position was higher than the LANK position for younger people in the z-direction during left heel contact, whereas the LTOE trajectory was lower for elderly people. Figure 9 shows the differences in LANK and LTOE between the elderly and young people at the time of left heel contact during one gait cycle. A value of 0 cm or more indicates that LTOE is higher than LANK, whereas a value of 0 cm or less indicates that the LTOE is lower. The mean values for the older and younger age groups

are shown. A *t*-test was performed, and a significant difference was found ($p < 0.01$) in the results shown in Figure 9, indicating that the elderly were unable to dorsiflex during heel contact. The results indicate that dorsiflexion of the foot is the cause of the angular change in θ_{foot} in elderly people within one gait cycle. This reduction in dorsiflexion in older adults during the swing phase suggests a higher risk of toe contact with obstacles, supporting research that suggests that measuring joint angles at key events/phases of the gait cycle is a useful indicator of age-related degeneration in the control of lower limb trajectories during obstacle-free walking [22].

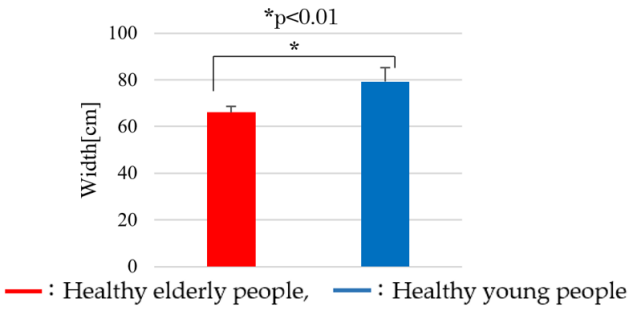

Figure 8. Swing in x-direction.

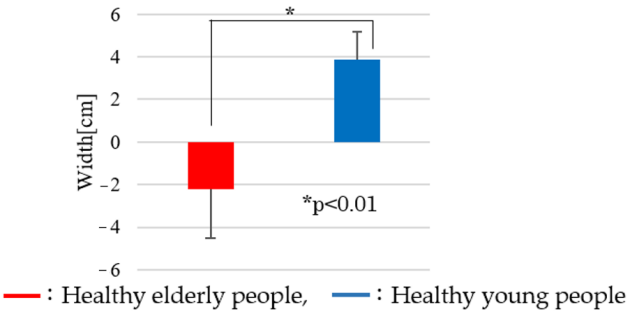

Figure 9. Width between LANK and LTOE at heel contact.

We examined the relationship between swing and kick-out in elderly and young people. A perpendicular line drawn from LASI to the ground was used as a reference line. The left side of the reference line was used for kick-out, and the right side was used for swing-out. Figure 10 compares the kick-out and swing-out of elderly and young people. There was no significant difference in the kick-out width, but there was a significant difference in the swing-out width ($p < 0.01$). These results indicate that the swing-out width is narrower for the elderly, supporting the fact that the age-related decrease in knee flexion is caused by muscle weakness [23].

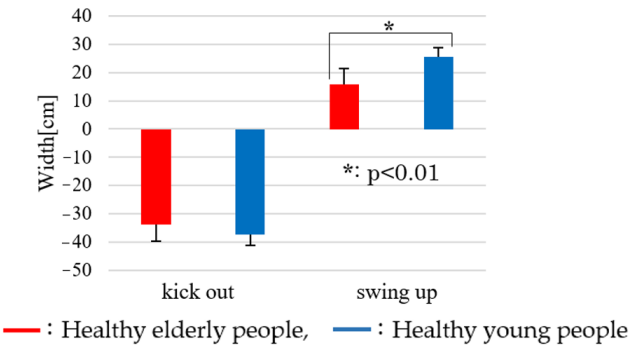

Figure 10. Differences of flexion swing and extension swing.

4.4. Knee Trajectory

A survey conducted in northwest Bristol, England, reported that 70.4% of men and 85.7% of women aged 55 years or older had knee pain [24]. Osteoarthritis is the most common cause of knee pain [7,8]. Osteoarthritis is a disease in which the cartilage and meniscus of the knee joint, which play a role in absorbing shock, wear away, and the bones become deformed, causing pain. Abnormal knee alignment is one of the causes of knee osteoarthritis. Knee alignment refers to the alignment and shape of the bones and joints. Patients with osteoarthritis of the knee generally have a deformity of the knee that is often called a "genu varum." Mechanical studies of the knee relating gait and knee angles during flexion and extension have been conducted [22,23,25]. Therefore, we focused on knee motion during gait, which has not been analyzed in detail.

The knee trajectories of healthy elderly patients tended to show less vertical movement and more lateral movement than those of healthy younger patients. The *t*-test results showed a significant difference ($p < 0.05$) in the lateral width of the left knee trajectory in one gait cycle from heel contact to re-grounding (Figures 11–13). There was no difference in the trajectory areas. This is because the trajectories of the healthy elderly patients had small vertical movements and large lateral movements, whereas those of the healthy younger patients had large vertical movements and small lateral movements.

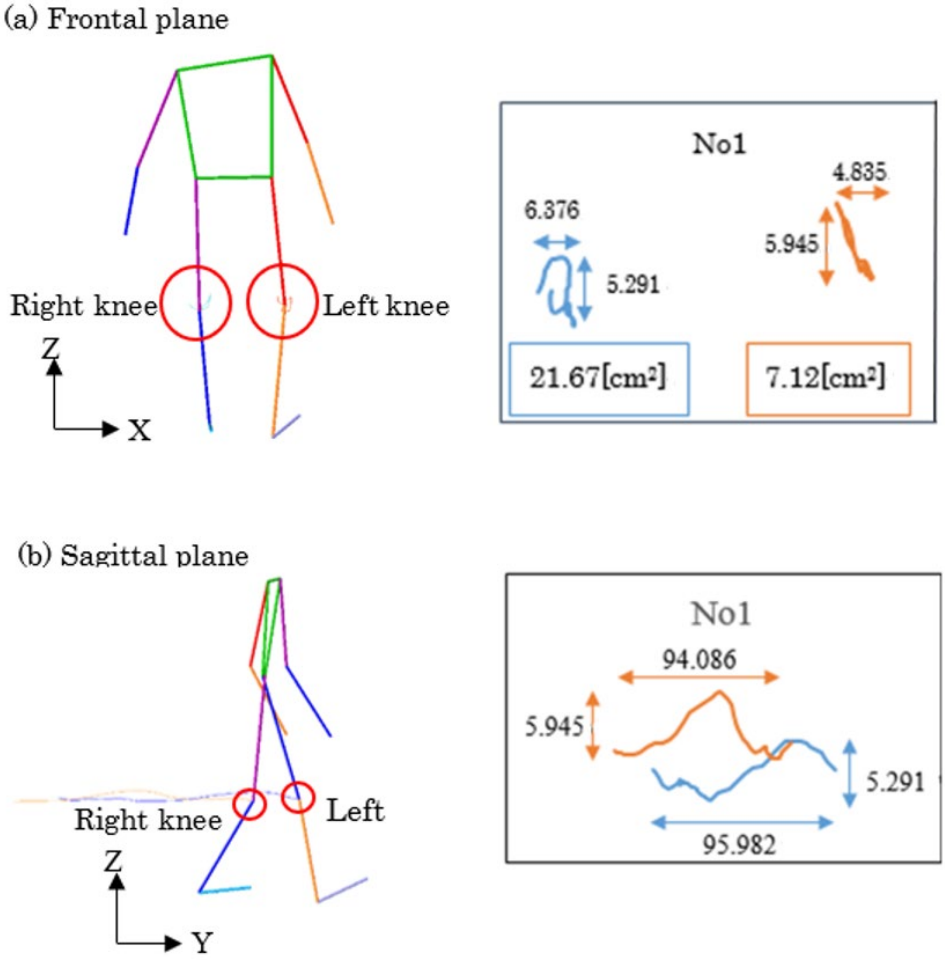

Figure 11. Knee trajectories.

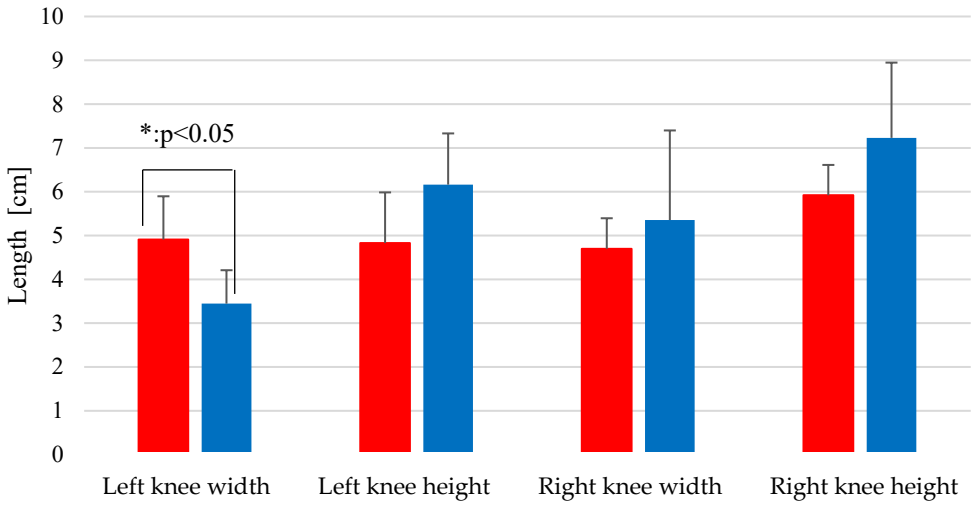

Figure 12. Mean widths and heights of the left and right knees.

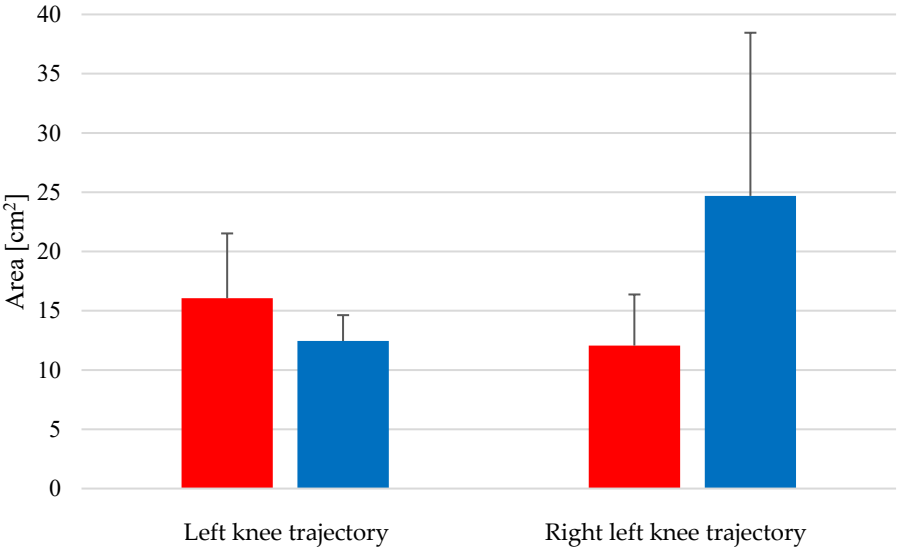

Figure 13. Mean area of left and right knee trajectories.

5. Discussion

To identify differences in lower limb movements during walking, motion capture was used to analyze the gaits of elderly and young people. Several studies on gait using elevation angles and PCLs have been conducted on a treadmill at a constant speed. We investigated gait at natural walking speeds with the aim of sensing changes in gait function in daily life. In this study, we first conducted GLFS-25 tests to confirm that there were no hindrances to walking. The experimental results showed that the plane rule holds true for both the elderly and the young. Furthermore, a predominant difference in the magnitude of the elevation angle, which was evident in a previous study using a treadmill, was also observed, with the elderly having a lower walking speed than younger people.

To examine the differences in the elevation angles in detail, we examined θ_{thigh}, θ_{shank}, and θ_{foot}. For all θ values, the difference between flexion and extension and between plantar flexion and dorsiflexion tended to be smaller in the elderly than in the younger patients, and there were significant differences between flexion and extension of θ_{shank} and between plantar flexion and dorsiflexion of θ_{foot}. The differences in elevation angle were attributed to flexion and extension of the θ_{shank} and plantar flexion and dorsiflexion of the θ_{foot}. These results showed clear differences in the sagittal trajectories of LASI, LKNE, LANK, and LTOE. For younger patients, the LTOE trajectory was higher than the LANK

trajectory for the left heel, while for older participants, the LTOE trajectory was lower than the LANK trajectory, indicating that older patients tend to walk with their legs less raised and shuffling with a shuffling gait. The angular change in θ_{foot} within a gait cycle was attributed to dorsiflexion of the foot. The relationship between swing-up and kick-out showed that the difference in swing-up was greater than that in kick-out.

6. Conclusions

Because maintaining walking ability is essential to maintaining QOL, we examined an index of walking posture characteristics to confirm changes in walking function in daily life. In this study, the plane covariance rule and the walking trajectory were examined based on the walking posture. As shown in Figure 3, we found that the plane covariance rule holds even when walking at one's own speed and that the PCL circle of the elderly is smaller than that of the young. This suggests that changes in walking function may be captured by the size and shape of the PCL circle. Furthermore, Figures 5 and 6 show that this is due to flexion and extension by θ_{shank} and plantar flexion and dorsiflexion due to θ_{foot}. In addition, the sagittal plane monitoring results shown in Figures 7–9 indicate that the elderly tend to walk with a shuffling gait and weak leg swing, suggesting the possibility of sensing changes in daily walking behavior.

In the future, we plan to repeat the experiments conducted in this study with an increased number of samples and with subjects who are mostly in stages 1 and 2 of the GLFS-25, and we will examine the relationship between flexion and extension muscle strength and plantar flexion and dorsiflexion muscle strength by measuring muscle potentials in order to identify the walking posture characteristics necessary for maintaining and improving walking ability.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and was approved by the Kwansei Gakuin University Medical Research Ethics Committee (No. KG-IRB-16-05) (26 April 2016).

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

Data Availability Statement: The data that support the findings of this study are available upon request from the corresponding author, N. Saga. The data are not publicly available due to the restriction that they contain information that requires the consent of the study participants.

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Conflicts of Interest: Author Mizuki Saga was employed by the company TMEIC Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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