

## Article

# The Effects of Structural Characteristics of the Rollator on the Elderly's Gait Strategies in Various Walking Environments

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**Abstract:** A rollator, one of the most widely used among walking assistance devices, can assist the elderly with stable walking in their daily lives. In this study, we investigated how the structural characteristics of two types of rollators affect the upper and lower extremity muscle activity and plantar pressure of the elderly in various walking environments. We quantified muscle activity (upper and lower limbs) and plantar pressure (mean force, peak pressure, and contact area) of 11 older adults walking in various environments (flat, obstacle, uneven, and sloped terrain) using two types of rollators. Upper extremity muscle activity was highest in the obstacle terrain and the uneven terrain, and a significant difference was found due to the structural differences of the rollator. Additionally, it was observed that lower extremity muscle activity and plantar pressure patterns appeared in accordance with the gait strategy to maintain stability in an unstable or inclined walking environment. In other words, it was confirmed that the weight of the rollator, the size of the wheel, grip type, and the auxiliary tools had a great effect on the upper and lower extremity muscle activity and plantar pressure of the elderly during walking. From the results of this study, it can be suggested that it is absolutely necessary to consider the biomechanical characteristics of the elderly and the structure of the rollator, which appear differently depending on the walking environment, in the development of walking aids. In the future, more clinical data will be collected, and based on this a rollator that can safely assist the elderly in various walking environments will be developed.

**Keywords:** elderly; rollator; electromyography; plantar pressure distribution; walking environment



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## 1. Introduction

As life expectancy increases and fertility rates decrease, the proportion of the elderly population is growing significantly worldwide [1]. In South Korea, where population aging is progressing at the fastest pace in the world, the proportion aged 65 or older accounted for 17.5% in 2020 and is expected to increase to 46.4% in 2070 [2]. As the elderly's desire for quality of life increases along with such rapid population aging, various studies on age-friendly products that can provide quality services to the elderly are being conducted [3].

For the elderly, walking ability is an essential factor for carrying out daily life and social activities. However, when sensory function, postural reflexes, and muscle strength deteriorate due to physical aging, the elderly's gait strategy changes [4]. Walking assistance devices such as a cane or walker are representative age-friendly products that provide psychological stability to the elderly who have difficulty walking normally and support safe activities by preventing falls [5]. Selecting an appropriate assist device is very important for walking safely in the elderly. It has been established that both the standard walker and wheeled walker (rollator), which can efficiently assist walking through extended supports, provide greater stability and mobility than canes [6]. Previous studies have compared and analyzed the differences between the two types of walkers in terms of biomechanics. So

et al. [7] reported that the wheeled walkers, rather than standard walkers which require lifting the device off the ground when walking, can help elderly people with reduced upper body strength maintain a natural walking pattern. Li et al. [8] compared the clinical effectiveness of two types of walkers and found that using wheeled walkers was faster and involved less energy expenditure than standard walkers. In addition, postural stability in older adults with muscle weaknesses and balance impairments were improved by the use of a rollator [6]. In other words, it was confirmed that using a rollator, which enables smooth movement with less effort than a standard walker, is more suitable for the elderly.

On the other hand, the use of walking aids can be a risk factor for falls in elderly people [5]. Additionally, it was reported that fall injuries occur mainly on uphill, downhill, uneven ground, and obstacle terrain [9]. Plantar pressure distribution and electromyography (EMG) measurements are widely used and useful clinical evaluation methods to evaluate foot load characteristics and lower extremity function during walking. In previous studies, the gait strategy of the elderly in various walking environments were investigated by analyzing biomechanical variables, including gait pattern, muscle activity, and plantar pressure. Ippersiel et al. [10] found that older adults' gait patterns were more variable during the initial stance phase and the middle swing phase to maintain stability and prevent falls when walking on uneven ground. Kwee-Meier et al. [11] revealed a walking strategy in the elderly that compensates for physical limitations by simultaneously activating lower extremity and pelvic muscles during forward propulsion during uphill walking. Based on analysis of lower limb muscle activity and plantar pressure, Kim et al. [12] confirmed that the pressure and contact time of the rearfoot increase to prevent falls that may occur due to unstable ankle movement when elderly people walk in an outdoor environment.

In recent years, with the development of technology, many studies related to intelligent wheeled walkers have been conducted. Arogunjo et al. [13] demonstrated the effectiveness of a robotic wheeled walker in improving gait and postural stability in patients with balance disorders. Matthies et al. [14] introduced a step detection algorithm for rollator users based on a three-axis accelerometer in smartwatches. Bieber et al. [15] presented the concept of an autonomous electro-powered rollator which can evaluate the mobility, stability, physical ability, and vital signs of the elderly. Zhao et al. [16] proposed a smart robotic walker that can safely assist walking by utilizing the gait information of the elderly collected through various sensors installed in the rollator. However, although independence and quality of life could be improved based on these advanced technologies, most smart walkers are expensive, heavy, and complicated for the elderly to use [17,18]. Research on smart walkers has generally been carried out by attaching various sensors or devices to the conventional rollators that are commonly used to provide useful functions to users. In other words, the structural characteristics of a walker, such as size, weight, and grip type, are essential factors that should be considered in the development of a smart walker. Walking assistance devices such as rollators can directly affect the elderly's gait, balance, and falls. Accordingly, analyzing the biomechanical changes that occur when using a rollator in various walking environments is critical for preventing falls and injuries in the elderly. Nevertheless, few studies have investigated the biomechanical changes in the elderly when using walking aids in various walking environments. Therefore, the purpose of this study is to evaluate muscle activity (upper and lower limbs) and plantar pressure distribution in order to understand the biomechanical characteristics of the elderly when using a rollator in various walking environments.

## 2. Methodology

### 2.1. Structural Characteristics of Rollator

To compare the biomechanical characteristics of using a rollator in various walking environments, two types of rollators commonly used by the elderly in daily life were selected. As shown in Figure 1, they were classified as the rollator with a bar handle (RBH) and the rollator with a horizontal handle (RHH). The two types of rollators differ in dimensions, weight, wheel diameter, wheel thickness, height adjustment method, and

grip type. The RBH is relatively small in length, width, weight, wheel diameter, and wheel thickness compared to the RHH but has a greater height adjustment range. There are also differences in the height adjustment and grip method. The RBH type has a screw that can be loosened and re-tightened to achieve the desired height, and the height of the RHH can be adjusted step-by-step by pressing a button. The RBH, which consists of a bar handle, can hold the rollator with various grips and control the brake system with one hand. On the other hand, since the RHH has a horizontal handle, the grip method is limited, and the brake system should be operated with both hands. The RHH also has lift pedals attached to the inside of each wheel that can lift the front wheel over obstacles.

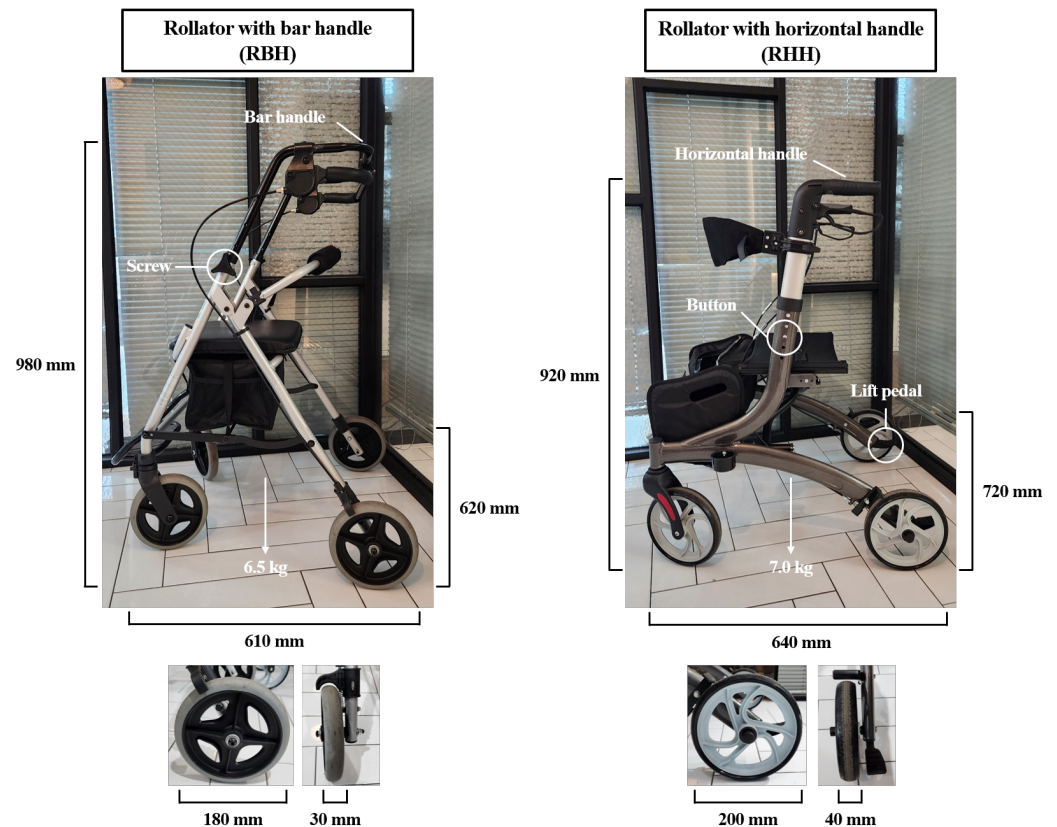


**Figure 1.** Structural differences between the two types of rollators.

## 2.2. Subjects

In this study, an experiment was conducted with 11 elderly people aged 65 years or older (age  $76.45 \pm 5.01$  years, height  $160.36 \pm 5.08$  cm, body weight  $57.91 \pm 9.18$  kg and body mass index  $22.44 \pm 2.58$  kg/m<sup>2</sup>, Mean  $\pm$  SD) who were able to walk and had experience using a rollator with a bar handle or horizontal handle. All subjects were recruited from the D senior welfare center located in Jeonju, Republic of Korea. Subjects with musculoskeletal disorders, back pain, and structural foot deformities, including flat feet or hallux valgus or varus, were excluded from the experiment. After explaining the purpose, procedure, and method of the experiment to the subjects, which was approved by Institutional Review Board of Jeonbuk National University, and obtaining each subject's signature on the informed consent form, the experiment was conducted.

## 2.3. Experimental Procedure

Various walking environments were produced to evaluate the walking strategy of the elderly when walking using rollators, as shown in Figure 2. The length of the walking environment was 7 m, and it was divided into flat terrain, obstacle terrain, uneven terrain, and sloped terrain. The flat terrain (FT) has no obstacles, uneven ground, or sloped ground. In the obstacle terrain (OT), three obstacles with a height of 2.5 cm were installed at 2 m

intervals on the left, right, and middle side of the walking path. In the uneven terrain (UT), eight mats 1.5 m long and 0.8 m wide, with gravel irregularly attached, were installed in a zigzag pattern. The sloped terrain consists of an uphill slope (US) and downhill slope (DS) with an inclination angle of 10 degrees. To carry out this study, after installing a structure composed of four terrains, older adults were allowed to walk using two different types of rollators. Then, based on the analysis results, we investigated how the structural differences in the rollator affect the elderly's gait strategy. Before the experiment, all subjects were instructed on how to use two types of rollators. Subjects were given as much time as needed to fully adapt to the rollators. The adaptation time for using the rollators was on average about 30 min. All subjects were asked to walk three times in each walking environment at a comfortable walking speed. Two types of rollators and four walking environments were randomly selected. To prevent fatigue, a 10 min break was allowed between each experimental condition. Considering that the material and shape of the shoe can affect the plantar pressure distribution, the subjects were asked to walk wearing same shoes with flat soles prepared in advance before the experiment.

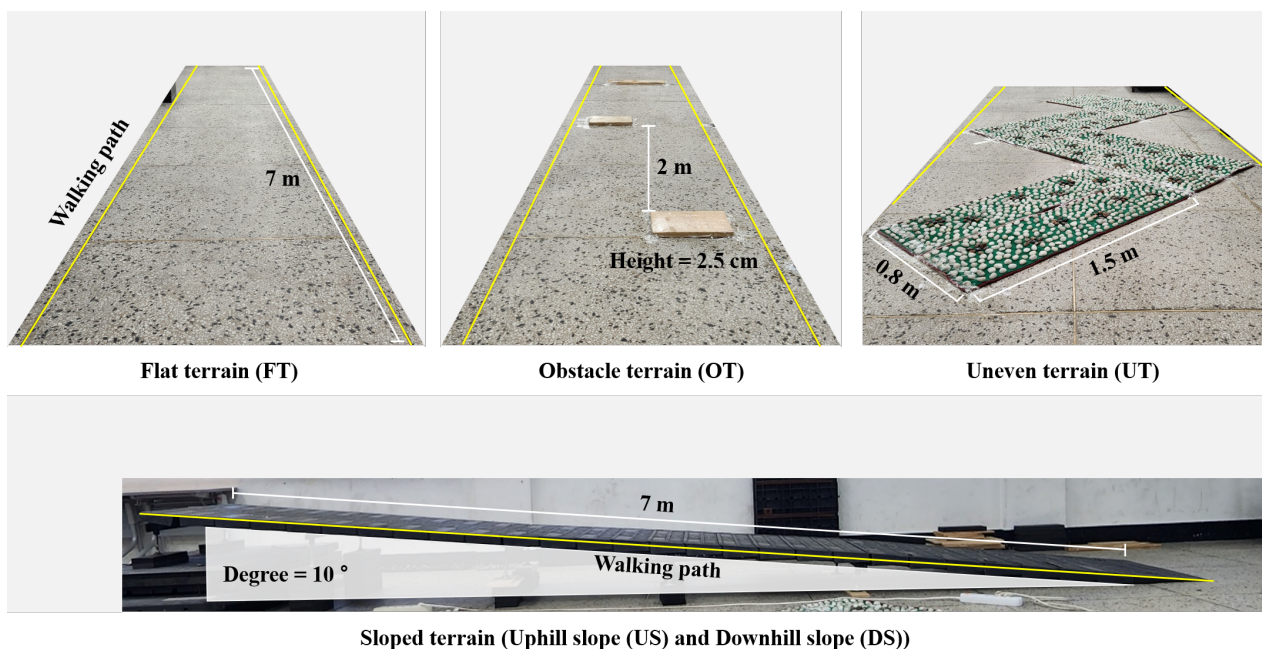


**Figure 2.** Walking environments.

#### 2.4. Experimental Setup

Muscle activity and plantar pressure distribution were measured to compare differences in biomechanical characteristics according to rollator types in various walking environments. As shown in Figure 3, surface electrodes were attached to the muscles of the upper and lower extremities, which are mainly activated when walking while holding the handle of a rollator, such as the flexor carpi ulnaris (FCU), extensor carpi radialis longus (ECRL), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius medialis (GM) muscles [19]. To reduce skin impedance that may occur during measurement, the appropriate area was cleaned with alcohol before attaching the surface electrode. The upper and lower extremity muscle activity was assessed with a Noraxon Desktop Direct Transmission System (Noraxon Inc., Scottsdale, AZ, USA), at a sampling rate of 1000 Hz. Plantar pressure distributions were assessed, at a sampling rate of 100 Hz, using a Pedar-X system (Novel GmbH, Munich, Germany) consisting of 99 capacitive sensors with thickness of 1.9 mm and a range of 15–600 kPa.

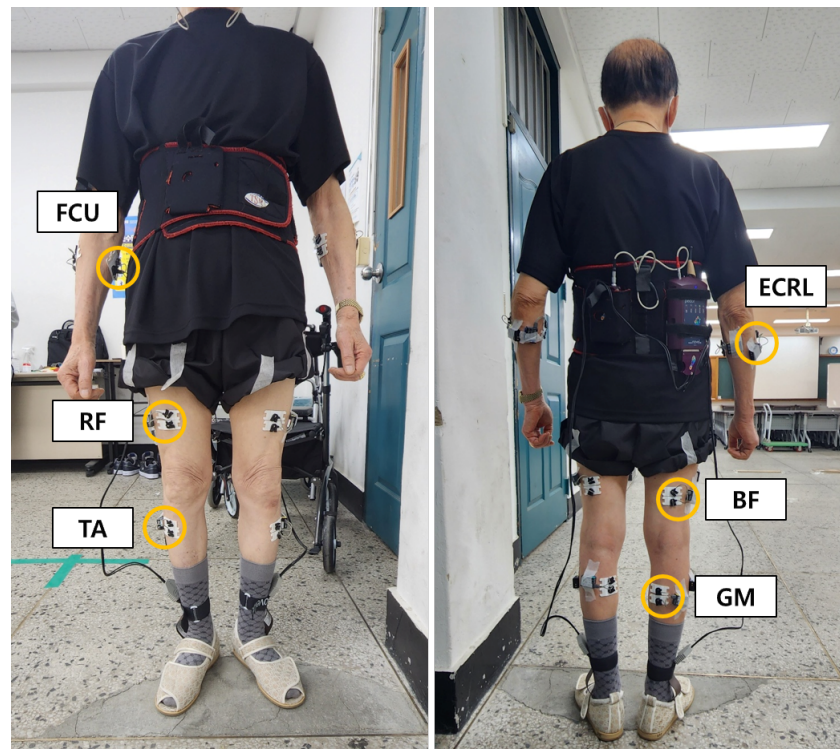


**Figure 3.** Surface electrode placement on the upper and lower extremity muscles.

### 2.5. Data Analysis

MyoResearch 3.6 software (Noraxon Inc., Scottsdale, AZ, USA) was used to analyze the muscle activity of the upper and lower extremity. Electromyographic (EMG) data were smoothed and rectified using root mean square (RMS) conversion with a window of 100 ms. The sixth-order Butterworth bandpass filter between 20 and 450 Hz was applied to the EMG signals. Then, data were filtered using a 6th-order Butterworth low-pass filter passing a 6 Hz cutoff frequency to generate a linear envelope [20]. In order to minimize errors in data analysis due to individual differences in muscle strength, normalization was conducted through a maximum voluntary contraction (MVC). Subjects were asked to perform 3 maximal contractions in 5 s, with 30 s rest between each repetition. The maximum muscle activation value collected over these three repeated measurements was considered as the MVC. The Pedar-X system software (Novel GmbH., Munich, Germany) was utilized to analyze the mean force, peak pressure, and contact area measured in the following five foot regions: hallux (H), lesser toes (LTs), forefoot (FF), midfoot (MF), and hindfoot (HF), as shown in Figure 4. The mean force was normalized to body weight (BW) for each subject. The contact area was normalized to the total contact area of the insole and therefore is reported in units of normalized insole contact area (NICA) [21].

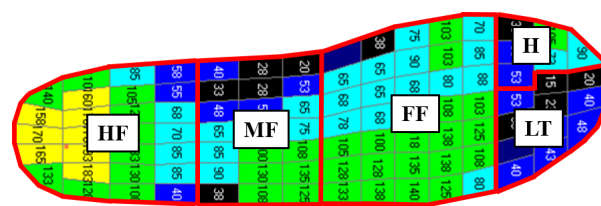


**Figure 4.** The foot area defined by five masks. H: hallux; LT: lesser toe region; FF: forefoot; MF: midfoot; HF: hindfoot.

### 2.6. Statistical Analysis

Statistical analysis was performed using SPSS software version 18.0. The normality of all variables was verified with the Shapiro–Wilk test. Then, a paired *t*-test was used

to compare the differences in upper and lower limb muscle activity and plantar pressure distribution according to the use of the two type of rollators. Additionally, one-way analysis of variance (ANOVA) with Tukey's post hoc test was performed to compare the results of upper and lower limb muscle activity and plantar pressure distribution measured in the four walking environments. Statistical significance was set to 0.05 and 0.01, respectively.

### 3. Results

#### 3.1. Muscle Activity

Table 1 shows the results of muscle activity of the upper and lower extremities when walking using two types of walkers under all experimental conditions. The results of muscle activity in the upper extremity are as follows. In the case of FCU, muscle activity was significantly increased in the OT, UT and US compared to the FT when walking using the RBH. On the other hand, there were significant decreases in muscle activity between the OT and US, OT and DS, UT and US, and UT and DS. When walking using the RHH, muscle activity significantly increased between the FT and UT, FT and US, FT and DS, and OT and UT, while it significantly decreased between the UT and DS. In the comparison of muscle activity between the RBH and RHH, when the RHH was used, it significantly decreased by 52.93% in the OT and 21.29% in the UT, while it significantly increased by 21.51% in the DS. In the case of the ECRL, muscle activity patterns during walking using the RBH and RHH showed similar trends. When walking using the RBH, muscle activity significantly increased in the UT compared to the FT and OT, respectively. On the other hand, it was significantly decreased in both the US and DS compared to the UT. When walking using the RHH, it was significantly increased between the FT and UT as well as between the OT and UT but significantly decreased between the UT and US. In the comparison of muscle activity between the RBH and RHH, when the RHH was used, it significantly decreased by 15.15% in the FT, 24.25% in the OT, 29.67% in the UT, 42.82% in the US, and 38.65% in the DS, respectively.

The results of muscle activity in the lower extremity are as follows. In the case of the RF, when walking using the RBH or RHH, there was no significant difference in muscle activity according to the walking environment. The lowest muscle activity was found in the OT. In the comparison of muscle activity between the RBH and RHH, when the RHH was used, it only significantly decreased by 8.55% in the UT. In the case of the TA, there was no significant difference in muscle activity according to the walking environment when walking using the RBH. On the other hand, when walking using the RHH, muscle activity was significantly decreased in the UT compared to the OT. In the comparison of muscle activity between the RBH and RHH, when the RHH was used, it significantly increased by 15.42% in the OT but significantly decreased by 15.22% in the UT. In the case of the BF, when walking using the RBH, muscle activity increased in all other walking environments compared to the FT, of which the greatest increase was observed in the UT. Similarly, when walking using the RHH, it increased in all other walking environments compared to the FT, but the largest increase occurred in the US. There was no significant difference in muscle activity according to the walking environment. In the comparison of muscle activity between the RBH and RHH, when the RHH was used, it significantly decreased by 10.28% in the OT and 9.03% in the UT, respectively. In the case of the GM, the magnitude of muscle activity according to the use of two types of walkers was the highest compared to other muscles. When walking with the RBH, muscle activity was significantly increased in the US compared to the OT and UT. When walking using the RHH, muscle activity significantly decreased in the OT compared to the FT, while it increased significantly in the US compared to the OT and UT. In the comparison of muscle activity between the RBH and RHH, when the RHH was used, it significantly increased only by 6.34% in the FT.

### 3.2. Plantar Pressure Distribution

#### 3.2.1. Mean Force

Table 2 shows the results of mean force when walking with two types of walkers under all experimental conditions. In the H region, mean force in the UT and US was significantly decreased compared to the FT when walking using both the RBH and RHH. On the other hand, it was significantly increased in the DS compared to all other walking environments. There were no significant differences in mean force between the two types of rollators. In the LT region, only when walking using the RBH was mean force significantly reduced in the UT and US compared to the FT. In contrast, when using both the RBH and RHH, the overall mean force increased significantly in the DS compared to the OT, UT, and US. In the comparison of mean force between the RBH and RHH, when the RHH was used, it significantly decreased by 5.13% in the FT but significantly increased by 7.69% in the UT. In the FF region, both types of walkers showed a pattern of significantly reduced mean force in all other walking environments compared to the FT. In the comparison of mean force between the RBH and RHH, when the RHH was used, it significantly increased only by 8.19% in the UT. In the MF region, mean force slightly increased in the OT and UT, while it slightly decreased in the US and DS. There was no statistically significant difference. However, in the comparison of mean force between the RBH and RHH, when the RHH was used, it only significantly increased by 9.09% in the OT. In the HF region, the differences in mean force among walking environments showed a similar pattern when walking using both the RBH and RHH. When walking using both the RBH and RHH, mean force in the DS was significantly decreased compared to other walking environments. Furthermore, when walking using the RBH, it significantly decreased in the US compared to the OT and UT. In the comparison of mean force between the RBH and RHH, when the RHH was used, it significantly decreased only by 9.39% in the UT.

**Table 1.** The results of muscle activity when walking with two types of walkers in various walking environments.

|          |     | FT             | OT                          | UT                              | US                              | DS                              |
|----------|-----|----------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|
| FCU (%)  | RBH | 8.409 ± 2.740  | 29.071 ± 5.621 <sup>a</sup> | 26.895 ± 4.717 <sup>b</sup>     | 16.121 ± 2.769 <sup>c,f,h</sup> | 12.420 ± 3.306 <sup>g,i</sup>   |
|          | RHH | 8.799 ± 2.972  | 13.683 ± 3.264 *            | 21.170 ± 5.269 <sup>b,e,*</sup> | 19.116 ± 5.968 <sup>c</sup>     | 15.091 ± 3.633 <sup>d,i,*</sup> |
| ECRL (%) | RBH | 17.623 ± 2.807 | 23.183 ± 2.933              | 34.829 ± 7.675 <sup>b,e</sup>   | 21.695 ± 3.958 <sup>h</sup>     | 23.896 ± 5.974 <sup>i</sup>     |
|          | RHH | 14.953 ± 3.509 | 17.561 ± 4.033 *            | 24.497 ± 4.853 <sup>b,e,*</sup> | 12.406 ± 2.821 <sup>f,h,*</sup> | 14.660 ± 2.752 <sup>i,*</sup>   |
| RF (%)   | RBH | 28.967 ± 4.206 | 26.415 ± 5.326              | 31.130 ± 5.052                  | 29.491 ± 4.814                  | 29.857 ± 5.155                  |
|          | RHH | 26.952 ± 4.609 | 24.884 ± 3.810              | 28.467 ± 4.598 *                | 29.428 ± 4.697                  | 27.829 ± 4.869                  |
| TA (%)   | RBH | 30.443 ± 4.751 | 28.850 ± 4.110              | 31.029 ± 4.608 <sup>e</sup>     | 30.140 ± 3.213                  | 25.517 ± 4.875                  |
|          | RHH | 30.192 ± 5.781 | 33.297 ± 3.940 *            | 26.305 ± 3.534 *                | 31.241 ± 4.758                  | 28.139 ± 4.304                  |
| BF (%)   | RBH | 28.617 ± 4.294 | 34.536 ± 6.540              | 36.481 ± 6.319                  | 32.305 ± 6.728                  | 31.757 ± 5.475                  |
|          | RHH | 28.652 ± 5.050 | 30.987 ± 4.391 *            | 33.187 ± 5.468 *                | 34.165 ± 7.822                  | 32.298 ± 5.478                  |
| GM (%)   | RBH | 35.648 ± 2.815 | 32.132 ± 3.209              | 33.725 ± 5.644                  | 40.592 ± 4.022 <sup>f,h</sup>   | 37.728 ± 5.690                  |
|          | RHH | 37.910 ± 3.300 | 31.647 ± 3.710 <sup>a</sup> | 32.277 ± 4.495                  | 38.458 ± 3.788 <sup>f,h</sup>   | 37.122 ± 6.184                  |

Notes: (M ± SD); <sup>a</sup>: Significant difference in muscle activity between the FT and OT ( $p < 0.05$  or  $p < 0.01$ ); <sup>b</sup>: Significant difference in muscle activity between the FT and UT ( $p < 0.05$  or  $p < 0.01$ ); <sup>c</sup>: Significant difference in muscle activity between the FT and US ( $p < 0.05$  or  $p < 0.01$ ); <sup>d</sup>: Significant difference in muscle activity between the FT and DS ( $p < 0.05$  or  $p < 0.01$ ); <sup>e</sup>: Significant difference in muscle activity between the OT and UT ( $p < 0.05$  or  $p < 0.01$ ); <sup>f</sup>: Significant difference in muscle activity between the OT and US ( $p < 0.05$  or  $p < 0.01$ ); <sup>g</sup>: Significant difference in muscle activity between the OT and DS ( $p < 0.05$  or  $p < 0.01$ ); <sup>h</sup>: Significant difference in muscle activity between the UT and US ( $p < 0.05$  or  $p < 0.01$ ); <sup>i</sup>: Significant difference in muscle activity between the UT and DS ( $p < 0.05$  or  $p < 0.01$ ); <sup>j</sup>: Significant difference in muscle activity between the US and DS ( $p < 0.05$  or  $p < 0.01$ ); \*: Significant difference in muscle activity between the RBH and RHH ( $p < 0.05$  or  $p < 0.01$ ).

### 3.2.2. Peak Pressure

Table 2 shows the results of peak pressure when walking with two types of walkers under all experimental conditions. In the H region, when walking using both the RBH and RHH, mean force was significantly increased in the DS compared to all other walking environments. However, there were no significant differences in peak pressure between the two types of rollators. In the LT region, when walking using the RBH, peak pressure was only significantly decreased in the UT compared to the FT. In contrast, compared to the DT, it was significantly increased in the OT, UT, and US. When walking using the RHH, peak pressure was also significantly decreased in the OT and UT except the US. In the comparison of peak pressure between the RBH and RHH, when the RHH was used, it significantly increased only by 7.45% in the UT. In the FF region, only when walking using the RBH was peak pressure significantly reduced in the OT and UT compared to the FT. In the comparison of peak pressure between the RBH and RHH, when the RHH was used, it significantly decreased by 3.43% in the FT and 4.24% in the DS but significantly increased by 6.62% in the UT. In the MF region, when walking using the RBH, peak pressure in the US was significantly decreased compared to the UT. Furthermore, it was significantly decreased in the DS compared to the OT and UT. When walking using the RHH, peak pressure in the OT was significantly increased compared to the FT. In contrast, it was significantly decreased in both the US and DS compared to the OT and UT, respectively. In the comparison of mean force between the RBH and RHH, when the RHH was used, it only significantly increased by 15.24% in the OT. In the HF region, when walking using the RBH, peak pressure was significantly decreased in the DS compared to all other walking environments. Similarly, when walking using the RHH, it was significantly decreased in the DS compared to the FT, OT, and UT. In the comparison of mean force between the RBH and RHH, when the RHH was used, it only significantly decreased by 7.71% in the UT.

### 3.2.3. Contact Area

Table 2 shows the results of contact area when walking with two types of walkers under all experimental conditions. Overall, the difference in contact area according to the walking environment in all regions showed a similar pattern. In the H region, contact area was significantly increased only in the US compared to the FT when walking using the RHH. When walking using both the RBH and RHH, it was significantly increased in the DS compared to all other walking environments. However, there were no significant differences in contact area between the two types of rollators. In the LT region, when walking using both the RBH and RHH, contact area was significantly increased only in the DS compared to all other walking environments. In the comparison of contact area between the RBH and RHH, when the RHH was used, it only significantly decreased by 0.99% in the FT. In the FF region, when walking using the RBH, contact area significantly decreased in the OT compared to the FT, while it increased in the DS compared to the OT and UT. Similarly, it significantly decreased in the OT compared to the FT, while it increased in the DS compared to the OT. In the comparison of contact area between the RBH and RHH, when the RHH was used, it only significantly increased by 2.15% in the FT. In the MF region, there was no significant difference in contact area between walking environments. Likewise, no significance was found in the contact area between the two types of rollators. In the HF region, when walking using the RBH, contact area was significantly increased in the OT and UT compared to the FT. In contrast, when walking using both the RBH and RHH, it was significantly decreased in the DS compared to all other walking environments. In the comparison of contact area between the RBH and RHH, when the RHH was used, it significantly decreased by 2.87% in the FT and by 8.1% in the UT, respectively.

**Table 2.** The results of plantar pressure distribution when walking with two types of walkers in various walking environments.

|                           |     |     | FT                 | OT                            | UT                           | US                            | DS                                  |
|---------------------------|-----|-----|--------------------|-------------------------------|------------------------------|-------------------------------|-------------------------------------|
| Mean<br>force<br>(N/kg)   | H   | RBH | 0.715 ± 0.124      | 0.584 ± 0.114                 | 0.498 ± 0.107 <sup>b</sup>   | 0.510 ± 0.103 <sup>c</sup>    | 0.905 ± 0.175 <sup>d,g,i,j</sup>    |
|                           |     | RHH | 0.688 ± 0.128      | 0.600 ± 0.104                 | 0.500 ± 0.114 <sup>b</sup>   | 0.510 ± 0.090 <sup>c</sup>    | 0.935 ± 0.189 <sup>d,g,i,j</sup>    |
|                           | LTs | RBH | 0.780 ± 0.149      | 0.604 ± 0.135                 | 0.516 ± 0.119 <sup>b</sup>   | 0.580 ± 0.110 <sup>c</sup>    | 0.829 ± 0.145 <sup>g,i,j</sup>      |
|                           |     | RHH | 0.738 ± 0.144 *    | 0.604 ± 0.135                 | 0.560 ± 0.142 *              | 0.639 ± 0.124                 | 0.829 ± 0.164 <sup>g,i,j</sup>      |
|                           | FF  | RBH | 3.025 ± 0.239      | 2.381 ± 0.238 <sup>a</sup>    | 2.318 ± 0.246 <sup>b</sup>   | 2.548 ± 0.267 <sup>c</sup>    | 2.619 ± 0.216 <sup>d</sup>          |
|                           |     | RHH | 2.947 ± 0.228      | 2.359 ± 0.177 <sup>a</sup>    | 2.511 ± 0.296 <sup>b,*</sup> | 2.625 ± 0.221 <sup>c</sup>    | 2.554 ± 0.219 <sup>d</sup>          |
|                           | MF  | RBH | 0.888 ± 0.303      | 0.994 ± 0.324                 | 1.045 ± 0.303                | 0.778 ± 0.244                 | 0.798 ± 0.315                       |
|                           |     | RHH | 0.864 ± 0.296      | 1.076 ± 0.281 *               | 1.039 ± 0.304                | 0.775 ± 0.244                 | 0.765 ± 0.296                       |
|                           | HF  | RBH | 3.183 ± 0.283      | 3.321 ± 0.237                 | 3.304 ± 0.274                | 2.873 ± 0.301 <sup>f,h</sup>  | 2.086 ± 0.252 <sup>d,g,i,j</sup>    |
|                           |     | RHH | 3.079 ± 0.330      | 3.153 ± 0.287                 | 2.988 ± 0.290 *              | 2.784 ± 0.306                 | 2.075 ± 0.261 <sup>d,g,i,j</sup>    |
| Peak<br>pressure<br>(kPa) | H   | RBH | 98.889 ± 19.800    | 84.809 ± 20.347               | 74.767 ± 18.358              | 74.372 ± 15.870               | 138.162 ± 39.642 <sup>d,g,i,j</sup> |
|                           |     | RHH | 93.716 ± 18.307    | 87.553 ± 21.044               | 77.584 ± 19.000              | 74.968 ± 14.636               | 138.332 ± 38.158 <sup>d,g,i,j</sup> |
|                           | LTs | RBH | 73.334 ± 13.278    | 59.605 ± 11.758               | 55.407 ± 11.804 <sup>b</sup> | 60.574 ± 11.568               | 79.932 ± 13.933 <sup>g,i,j</sup>    |
|                           |     | RHH | 71.828 ± 13.331    | 61.329 ± 10.855               | 59.545 ± 12.985 *            | 64.246 ± 12.589               | 81.002 ± 13.326 <sup>g,i</sup>      |
|                           | FF  | RBH | 116.477 ± 16.505   | 93.276 ± 13.376 <sup>a</sup>  | 90.891 ± 12.924 <sup>b</sup> | 103.684 ± 14.076              | 104.421 ± 14.709                    |
|                           |     | RHH | 112.484 ± 15.505 * | 93.290 ± 12.630               | 96.905 ± 15.147 *            | 106.200 ± 15.461              | 99.986 ± 13.540 *                   |
|                           | MF  | RBH | 51.982 ± 6.452     | 56.435 ± 6.979                | 59.692 ± 7.095               | 48.382 ± 7.404 <sup>h</sup>   | 45.947 ± 7.630 <sup>g,i</sup>       |
|                           |     | RHH | 50.712 ± 7.013     | 65.035 ± 7.372 <sup>a,*</sup> | 59.436 ± 7.631               | 48.519 ± 7.783 <sup>f,h</sup> | 44.811 ± 8.481 <sup>g,i</sup>       |
|                           | HF  | RBH | 95.530 ± 9.907     | 94.408 ± 9.458                | 98.938 ± 9.708               | 88.443 ± 10.935               | 71.456 ± 8.701 <sup>d,g,i,j</sup>   |
|                           |     | RHH | 94.138 ± 12.109    | 95.671 ± 11.330               | 91.313 ± 9.206 *             | 86.362 ± 11.686               | 71.402 ± 10.676 <sup>d,g,i</sup>    |

Table 2. Cont.

|                           |     | FT  | OT                         | UT                         | US                         | DS                         |                                  |
|---------------------------|-----|-----|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------------|
| Contact<br>Area<br>(NICA) | H   | RBH | 0.069 ± 0.007              | 0.063 ± 0.007              | 0.063 ± 0.008              | 0.060 ± 0.007              | 0.088 ± 0.008 <sup>d,g,i,j</sup> |
|                           |     | RHH | 0.070 ± 0.008              | 0.066 ± 0.006              | 0.060 ± 0.008              | 0.059 ± 0.007 <sup>c</sup> | 0.087 ± 0.009 <sup>d,g,i,j</sup> |
|                           | LTs | RBH | 0.101 ± 0.013              | 0.089 ± 0.013              | 0.088 ± 0.016              | 0.091 ± 0.012              | 0.126 ± 0.014 <sup>d,g,i,j</sup> |
|                           |     | RHH | 0.100 ± 0.014 <sup>*</sup> | 0.093 ± 0.011              | 0.086 ± 0.014              | 0.098 ± 0.014              | 0.126 ± 0.017 <sup>d,g,i,j</sup> |
|                           | FF  | RBH | 0.372 ± 0.021              | 0.328 ± 0.024 <sup>a</sup> | 0.351 ± 0.022              | 0.357 ± 0.022              | 0.384 ± 0.020 <sup>g,i</sup>     |
|                           |     | RHH | 0.380 ± 0.022 <sup>*</sup> | 0.343 ± 0.020 <sup>a</sup> | 0.358 ± 0.022              | 0.365 ± 0.021              | 0.381 ± 0.022 <sup>g</sup>       |
|                           | MF  | RBH | 0.144 ± 0.024              | 0.162 ± 0.030              | 0.169 ± 0.029              | 0.148 ± 0.027              | 0.142 ± 0.025                    |
|                           |     | RHH | 0.144 ± 0.026              | 0.164 ± 0.026              | 0.166 ± 0.028              | 0.149 ± 0.026              | 0.142 ± 0.027                    |
|                           | HF  | RBH | 0.314 ± 0.022              | 0.358 ± 0.018 <sup>a</sup> | 0.358 ± 0.025 <sup>b</sup> | 0.344 ± 0.031              | 0.260 ± 0.021 <sup>d,g,i,j</sup> |
|                           |     | RHH | 0.305 ± 0.025 <sup>*</sup> | 0.334 ± 0.018              | 0.329 ± 0.020 <sup>*</sup> | 0.329 ± 0.023              | 0.263 ± 0.026 <sup>d,g,i,j</sup> |

Notes: (M ± SD); <sup>a</sup>: Significant difference in mean force between the FT and OT ( $p < 0.05$  or  $p < 0.01$ ); <sup>b</sup>: Significant difference in mean force between the FT and UT ( $p < 0.05$  or  $p < 0.01$ ); <sup>c</sup>: Significant difference in mean force between the FT and US ( $p < 0.05$  or  $p < 0.01$ ); <sup>d</sup>: Significant difference in mean force between the FT and DS ( $p < 0.05$  or  $p < 0.01$ ); <sup>e</sup>: Significant difference in mean force between the OT and UT ( $p < 0.05$  or  $p < 0.01$ ); <sup>f</sup>: Significant difference in mean force between the OT and US ( $p < 0.05$  or  $p < 0.01$ ); <sup>g</sup>: Significant difference in mean force between the OT and DS ( $p < 0.05$  or  $p < 0.01$ ); <sup>h</sup>: Significant difference in mean force between the UT and US ( $p < 0.05$  or  $p < 0.01$ ); <sup>i</sup>: Significant difference in mean force between the UT and DS ( $p < 0.05$  or  $p < 0.01$ ); <sup>j</sup>: Significant difference in mean force between the US and DS ( $p < 0.05$  or  $p < 0.01$ ); \*: Significant difference in mean force between the RBH and RHH ( $p < 0.05$  or  $p < 0.01$ ).

#### 4. Discussion

When two types of rollators were used in various walking environments, the measured FCU activity was high in all other environments compared to the FT. The FCU is a muscle that is primarily used when flexing the wrist forward or inward [22]. Differences in muscle activity between the two types of rollators appeared in the OT with an obstacle, UT with an uneven ground, and DS with a downhill slope. In general, in the OT and UT, more force is used than in other walking environments when lifting a walker or adjusting it in a desired direction due to the characteristics of the terrain. In particular, if the wheel size or thickness is small, it may not be easy to overcome high obstacles or bumpy gravel roads. For this reason, it is considered that the activity of the FCU was further increased in the RBH, which has a relatively small wheel size and thickness. In addition, when the RHH was used, muscle activity decreased significantly in the OT and UT but increased slightly in the US and DS. It may be considered that the increased activity of the FCU when the RHH is used on a sloped terrain is due to the movement of the wrist joint to maintain a constant distance between the user and the rollator.

ECRL activities related to wrist extension and abduction were the highest in the UT with uneven ground. It is believed that this increase in muscle activity stably holds the rollator moving irregularly due to the uneven ground and adjusts it in the desired direction. This is consistent with previous findings that ECRL activity gradually increased with increasing grip strength [23]. In addition, as a result of comparing the activities of ECRL measured when using the RBH and RHH, it was confirmed that all activities were significantly decreased in RHH. The results of significant reductions in muscle activity when using the RHH suggest that wheel size, thickness and weight can have significant effects on wrist extension and abduction. In other words, the fact that the structural characteristics of the rollator directly affect the activity of the upper limb muscles can be confirmed through the difference in activity of the flexor and extensor muscles measured when using the two types of rollators. The RHH is equipped with a commonly used horizontal handle and lift pedals to help it avoid or overcome obstacles. Therefore, it is thought that these structural characteristics may have affected the reduction in muscle activity in the OT with obstacles or UT with irregularly placed gravel. In previous studies, it was reported that when walking while holding the handle of a walker, not only the flexor muscles but also the wrist extensor muscles were activated, canceling the wrist flexion torque caused by the finger flexor tendons [19]. In this study, we confirmed that the upper extremity muscle interaction can appear differently depending on the structural characteristics of the rollator and the walking environment. Excessive force, repetitive work, and vibration that can occur depending on the walking environment can be major factors that cause musculoskeletal disorders [24]. Therefore, in order to prevent musculoskeletal disorders and improve user convenience, the design of walking aids considering the user and the walking environment is very important.

The measured RF activity showed similar trends for both the RBH and RHH. The RF is a muscle that plays an important role in controlling the extension of the knee joint, and its activity increases as the walking speed increases [25]. In the OT, where obstacles must be avoided or overcome while walking, RF activity is thought to decrease relative to other walking environments as walking speed slows. Conversely, in the UT, the RF contribution appears to be increased to prevent inappropriate foot–ground contact due to ground characteristics. The significant reduction in RF activity when using the RHH compared to the RBH suggests that a rollator, with its relatively large wheels and heavy weights, ensures adequate contact between the foot and ground during walking [25].

The TA, the largest dorsiflexor of the ankle joint, plays an important role in foot stabilization and postural control during walking [26]. The significant increase in TA activity that occurred with the use of the RHH in the OT is thought to be due to increased sagittal motion of the ankle using the lift pedal to overcome an obstacle [27]. On the other hand, it is estimated that the relatively large wheel compared to the RBH affected the reduction in muscle activation while facilitating movement on uneven ground such as UT.

Interestingly, TA activity decreased in the DS when using both types of rollators. Previous studies have confirmed that sloped walking leads to altered lower limb muscle forces [28]. The balance is to keep the center of mass (CoM) within the limits of the base of support (BoS). Accordingly, it is presumed that the use of a rollator increases BoS during walking and maintains proper balance, contributing to a significant reduction in TA activity [29].

The BF is mainly involved in the knee flexion [11]. The increased muscle activity in the OT and UT measured when using the RBH is thought to ensure gait stability in environments with obstacles or uneven ground. Our findings are commonly in line with a previous study which found that BF plays an important role in maintaining dynamic postural stability in older adults during walking [30]. It is suggested that the significant decrease in BF activity during the use of the RHH was influenced by the structural characteristics of the walker, which has a lift pedal and relatively large wheels. A previous study has reported that the elderly need more lower extremity muscle activity when walking on an uphill slope than on a flat road [31]. Therefore, it can be considered that the activity of the BF was higher in the US when walking with the RHH, which is heavier than the RBH.

The GM not only acts as a plantar flexor in the late stance phase but also as a knee flexor, performing as an antagonist during knee extension [32]. In this study, GM showed similar activity patterns in both the RBH and RHH depending on the walking environment. The significant increase in GM activity in the FT when using the RHH is thought to be due to the increased weight of the rollator requiring more forward propulsion. The biggest activity of GM can be found in the US. This is consistent with previous findings that observed greater activation of the gastrocnemius muscle in the elderly group during uphill walking [33,34]. It is believed that this rapid increase is also caused by generating additional force to push the rollator forward during uphill walking. Walking on an inclined terrain is a locomotion activity that requires complex adaptations to maintain stability [35]. In addition, it was found that inclined walking was associated with a higher risk of falling in the elderly than walking on stairs with a similar inclination [36]. Accordingly, increased muscle activity during uphill walking is thought to maintain a stable posture on an incline.

As a result of comparing the mean force, peak pressure, and contact area measured when using two types of rollators in various walking environments, similar patterns were found in the H and LT regions. The mean force, peak pressure, and contact area all decreased in the OT, UT, and US compared to the FT, while significant differences were most evident in mean force. This means that a large reduction in mean force has a direct effect on peak pressure and contact area. Decreased plantar pressure distribution in the H, LT, and FF regions could be associated with the lowest GM activity in the UT. During walking, the foot contributes to generating propulsion to move forward while adapting to the irregular surface [37]. Balance and gait are very important considerations for the health of older adults [38]. When walking using a walking aid, if there is an obstacle, deformation, or slope in the ground, the elderly use a walking strategy to keep the stability and postural balance for avoiding falling. These changes contribute to decreased plantar pressure in the feet and a slower walking speed. In particular, on irregular road surfaces, the elderly show a cautious gait pattern with slow gait speed, decreased stride length, and increased variability in stride timing [39]. So, it is believed that the pressure in the H, LT, and FF regions was affected as the walking speed and forward propulsion force decreased to maintain balance on rough ground. Additionally, when using the RHH, the LT and FF regions showed an increase in mean force and peak pressure compared to the RBH. These results are thought to be due to the changes in plantar pressure distribution in the elderly, whose weight shifts to the lateral side of the foot during walking while the weight of the rollator affects forward movement or direction control [40]. When walking on a downhill slope using two types of rollators, mean force, peak pressure, and contact area in the H and LT regions significantly increased compared to other walking environments. In previous research, as a result of analyzing the peak pressure of the foot according to the slope during downhill walking, it was reported that the pressure of the hallux region increased while the pressure of the lesser toes region decreased as the slope increased [41]. The plantar pressure

in the H, LT, and FF regions significantly increased during downhill walking, which may be related to the result of increased upper and lower extremity muscle activity. That is, when walking downhill using a rollator, it can be considered that stability is maintained by using a gait strategy in which muscles of the upper and lower limbs are activated, and force is applied to the toes until the moment the foot leaves the ground. Furthermore, forefoot pain, which is common in older people, is often caused by high pressure under the forefoot [42]. In particular, the peak pressure on the hallux region is the highest compared to other regions when walking downhill, which means that continuous use of a walker can cause foot injuries or pain of the elderly. Therefore, it is necessary to design the structure of the rollator to reduce forefoot pain by redistributing high forefoot plantar pressure.

For the results in the MF and HF regions, the mean force, peak pressure, and contact area measured in the OT and UT all increased. Previous studies analyzing the gait characteristics of the elderly reported an increase in support time and a decrease in movement speed from the initial stance phase to the middle stance phase for stable gait [43]. Accordingly, it could be confirmed that total plantar pressure distribution, not local pressure, increased while using the cautious gait strategy to stably maintain dynamic balance in an environment with obstacles or uneven ground. This gait strategy involves lower extremity muscle outcomes in which RF and BF are activated to maintain postural stability. When using the RHH in the OT, the significant increase in mean force and peak pressure in the MF region compared to the RBH is thought to be due to the use of the “lift pedal” mounted on the RHH. It is also thought that the reduced RF and TA activity during walking using the RHH with large wheels in the UT affected the mean force, peak pressure, and contact area between the hindfoot and the ground. In the elderly, downhill walking is a challenging daily mobility activity that requires complex adaptations to maintain gait stability [44]. From the results of the foot region, it can be confirmed that the mean force, peak pressure, and contact area when walking on a downhill terrain are relatively low compared to other walking environments. It has been found that walking downhill is associated with a higher risk of falling than walking up stairs because it significantly reduces walking stability [45]. The significantly lower plantar pressure distribution in the HF region may be considered to be due to the decrease in dorsiflexion and TA activity while reducing the stride length to ensure gait stability. This is consistent with previous findings that dorsiflexion at initial contact and midstance during downhill walking are significantly decreased by reduced step length [46].

There are some limitations with this study. First, walking aids are assistive devices used by a variety of people regardless of age or gender. Therefore, it is important to understand how the structure of the walking aid affects the user's age and gender. However, in this study, the sample size is relatively small, making it impossible to compare and analyze differences by age or gender. Second, research on walking aids should be prioritized for patients who need gait rehabilitation due to disease or surgery. However, since this study recruited active and healthy elderly people, it is difficult to apply the results to patients who need gait rehabilitation due to disease or surgery. Third, when using a rollator on an actual walking path, measuring muscle activity and plantar pressure distribution can provide more accurate information. Accordingly, various walking paths similar to the real environment were produced, but there were time, space, and cost limitations. Consequently, further studies are needed to recruit more elderly people and evaluate the various biomechanical characteristics that appear when using a manual/electric rollator in an actual walking environment.

## 5. Conclusions

A rollator is a very important device that assists the walking ability of elderly people in various walking environments. Depending on the walking environment, the weight, wheel size, and grip type of the walker can directly affect the walking strategy of the elderly. These findings can be of great help in developing walking aids suitable for the user's walking environment. In addition, the latest sensing technology can be applied to user-customized

devices and used for various purposes such as rehabilitation, treatment, and prevention. In future research, we will develop a rollator that can provide convenience and safety to the elderly in various walking environments and evaluate the effect on healthcare.

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