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Kinetic and Kinematic Analysis of Gait Termination: A Comparison between Planned and Unplanned Conditions

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Abstract: Purpose: Gait termination (GT) is the transition from steady-state walking to a complete stop, occurring under planned gait termination (PGT) or unplanned gait termination (UGT) conditions. This study aimed to investigate the biomechanical differences between PGT and UGT, which could help develop therapeutic interventions for individuals experiencing difficulty with GT. Methods: Twenty healthy adults performed three walking trials, followed by PGT and UGT trials. Gait termination was analyzed in three phases as follows: Phase 1 (pre-stopping), Phase 2 (initial stopping phase), and Phase 3 (terminal stopping phase). Spatiotemporal, kinematic, and kinetic data during each phase were compared between conditions. Results: The GT time and GT step length were significantly different between the PGT and UGT trials. Ankle range of motion (ROM) demonstrated significant differences in Phase 1, with the PGT having a slightly lower ankle ROM than the UGT. In Phase 2, the hip, knee, and ankle ROM exhibited significant differences between the conditions. Finally, in Phase 3, UGT showed reduced hip ROM but increased knee ROM and kinetic parameters compared to PGT. Conclusion: Our results indicate that the ankle joint primarily contributes to deceleration during the initial preparation for generating braking force during PGT. Conversely, UGT reveals disrupted kinesthetic control due to instability, leading to a preference for a hip and knee strategy to absorb force and control the center of mass for a safe and rapid GT in response to unexpected stimuli. These findings provide valuable insights into the biomechanical mechanisms underlying body stability during GT and may contribute to the development of effective rehabilitation strategies for individuals with gait impairment.

Keywords: gait termination; motion capture system; response inhibition

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1. Introduction

Gait termination (GT) corresponds to the transition from steady-state walking to complete stopping [1]. It requires braking forces and postural control, which are necessary to stop the forward momentum, demanding interaction between the biomechanical and neuromuscular systems [2]. GT can be divided into planned gait termination (PGT) and unplanned gait termination (UGT) according to the environmental conditions. PGT refers to the movement reaching or approaching the expected location determined by the interaction between an individual and environmental constraints [3]. In contrast, UGT (i.e., sudden stopping) is a response to unexpected external stimuli that requires the urgency of spontaneous activation of dynamic stability for a complete stop [4]. Gait termination ability is essential for an individual's safety, to decrease the risk of falling or prevent collision with another person or object under both conditions [5].

Previous studies have reported differences in the mechanisms between these two conditions. PGT relies on a feedforward system to stop at the desired target, whereas

UGT relies on a feedback system to control the body's center of mass in response to unexpected external stimulation [6]. The differences in the feedback systems between PGT and UGT could affect biomechanical and neuromuscular responses [7]. In PGT, anticipation is possible, leading to increased stopping time, decreased force development rate, and peak posterior braking force compared to UGT [4,8]. In contrast, UGT requires the body to increase the braking force and decrease propulsion for a short period to generate a sufficient net braking impulse compared with PGT [4,8]. Therefore, different joint kinematics are required for PGT and UGT.

Many studies have reported on the mechanisms of PGT and UGT using various analyses, including joint kinematics, and kinetics [9–12]. However, in these studies comparing the two conditions, only the main braking force that occurred during the stopping phase was analyzed. The mechanism of GT has been well-studied; however, studies analyzing biomechanical data by dividing the phases of gait termination, including the pre-stopping phase, are poorly understood. In addition, a previous study on PGT found that gait termination requires an increase in braking impulse and a concomitant decrease in propulsion with a double stance before the stopping phase [2,13]. Therefore, the pre-stopping phase may play a major role in the braking control process.

Our study aimed to investigate biomechanical data during the pre-stopping, initial stopping, and terminal stopping phases of the leading limb to understand the mechanism that prepares and generates braking force in UGT and PGT. We hypothesized that there would be differences in the gait parameters and braking force for stopping strategies depending on the stopping phase. Understanding the biomechanical characteristics of the stopping process may provide information that will be helpful in designing therapeutic interventions for individuals with difficulties with GT.

2. Methods

2.1. Subjects

Twenty healthy adults (ten males and ten females; mean age: 23.95 ± 2.56 years; mean height: 168.90 ± 8.44 cm; mean weight: 64.55 ± 12.95 kg; mean leg length: 86.55 ± 4.54 cm) were recruited for the study. The sample size was calculated using G-power software (G*power 3.1.9.7, Heinrich-Heine-Universität, Düsseldorf, Germany). With an effect size of 0.3, a significance level of 0.05, and a power of 0.80, a minimum of 20 participants was adequate to power the study. None of the participants had a history of musculoskeletal, neurological, or psychiatric diseases that could have affected their gait termination. All subjects completed the self-selected walking trial and two stopping trials: UGT and PGT conditions. All participants provided written informed consent, in accordance with the Declaration of Helsinki. This study was approved by the Institutional Review Board of Dankook University (DKU 2021-03-062).

2.2. Measurements

2.2.1. Motion Analysis System

A six-infrared-camera motion analysis system (Qualisys AB, Goteborg, Sweden) was used to analyze three-dimensional motion, with a sampling rate of 100 Hz [14]. Reflective markers were attached to anatomical landmarks to create a lower extremity model. The Anatomical markers were placed on the anterior superior iliac spine, posterior superior iliac spine, thigh, lateral epicondyle of the femur, medial epicondyle of the femur, shank, lateral malleolus, medial malleolus, calcaneus, and 1st, 2nd, and 5th metatarsal joints according to the CAST model [15]. Static trials were used to define the transformation between the marker arrays and the segment coordinate system.

Visual 3D (C-motion, Inc., Germantown, MD, USA) was used to analyze the spatiotemporal (gait velocity, stride length, normalized stride length, GT time, and GT step length) and kinematic (range of motion (ROM) of the hip, knee, and ankle joints) parameters [16]. The trajectories of the reflective markers were filtered using a second-order low-pass Butterworth filter with a cut-off frequency of 6 Hz.

2.2.2. Force Plates

Kinetic data during the stopping process were collected from two 400 mm × 600 mm force plates (Bertec Corp., Worthington, ON, USA) embedded in the floor at a sampling rate of 1000 Hz. The two force plates were synchronized using a motion analysis system. We mainly analyzed the data of the anterior–posterior ground reaction force because it is associated with propulsive and braking forces in the stopping process. Data on the peak anterior–posterior ground reaction force (GRF-y) and braking force (GRF-y impulse) were collected when gait termination was completed. The braking force was calculated as the area under the negative GRF-y component, and absolute values were used. The GRF data were normalized to the body mass of each individual [17,18].

2.2.3. Experimental Procedure

Demographic data, including height, weight, and leg length, were collected before data collection. The researchers attached reflective markers to the subjects for biomechanical measurements. Four familiarization trials were conducted to adjust the starting position before beginning each stopping trial. This enhanced the probability of the foot of the dominant limb being in contact with the first force plate correctly. The starting position was at least four steps away from the first force plate to ensure a self-selected speed. First, each subject performed three walking trials at their self-selected speed along a 10 m walkway without providing a stop signal. The subjects then performed stopping trials in a random order under two different conditions, PGT and UGT, both at their preferred speed [19,20]. The stopping trials were performed similarly to the walking trials, but the subjects were asked to stop upon reaching the force plates [19,20]. That is, their leading limb finished on the second force plate and their trailing limb finished on the ground beside the force plate (PGT condition) or on the first force plate (UGT condition), after which they were required to bring their trailing limbs parallel and maintain an upright standing posture for at least 3 s. In addition, they were asked not to slow down their gait before reaching the force plate [11]. If the participants appeared to have reduced their gait velocity before reaching the force plate, the trial was not analyzed. The trials were repeated until three valid trials were completed.

In the UGT condition, the participants were asked to stop immediately within one step using an auditory signal, without being told beforehand which force plate to stop on. The subjects were asked to "freeze" with their leading limb as soon as they heard the stop signal and then remain in that position for at least 3 s. The auditory stop signal was randomly triggered when the trailing limb contacted the first force plate, that is, GRF-z exceeded 50 N. To prevent the participants from predicting when to stop walking and to eliminate the learning effect, 25% of the UGT trials included the stop signal, whereas the remaining 75% did not contain a stop signal [4]. At least three trials were conducted when the leading limb landed on the second force plate without excessive steps and deceleration. Data were analyzed only when both feet were successfully placed on their respective force plates [19]. There was a 10-min rest interval between the PGT and UGT conditions to reduce the effects of fatigue on the experimental results. The PGT and UGT conditions were counterbalanced across the participants to minimize potential order effects (Figure 1).

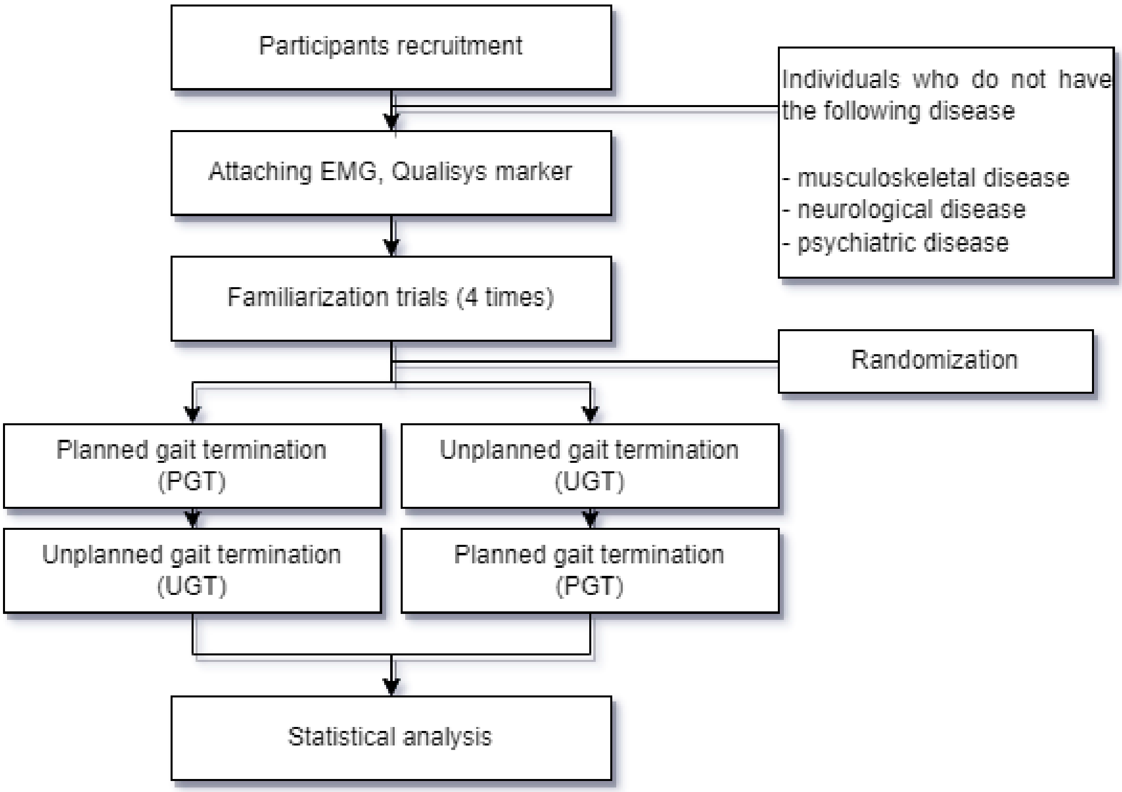

Figure 1. Flowchart of the experimental procedure.

2.2.4. Data Analysis

Gait termination was defined as when the center of mass (COM) progression velocity was less than 0.05 m/s in the anteroposterior (AP) direction [18]. In this study, gait termination was divided into three phases based on the identifiable vertical ground reaction force (GRF-z) landmarks [21]. Phase 1 was set from the time when the heel of the trailing limb made contact with the first force plate until the GRF-z of the trailing limb reached the mid-stance valley. Phase 2 was set from when the GRF-z of the trailing limb reached the mid-stance valley until the heel of the leading limb reached the second force plate. Phase 3 was set from when the heel of the leading limb made contact with the second force plate until the COM progression velocity falls below 0.05 m/s in the AP direction. Therefore, Phase 1 corresponds to the pre-stopping phase, in which gait deceleration occurs, and Phases 2 and 3, where the main braking occurs, correspond to the initial and terminal stopping phases, respectively (Figure 2). We mainly analyzed the data of the leading limb in each phase because the leading limb plays a more important role in gait termination than the trailing limb. The gait termination time was defined as the time interval between Phases 1 and 3. The gait termination step length was calculated as the AP distance between the trailing and leading limb heel contacts. The gait termination step length was normalized to an individual's leg length. Gait velocity was calculated by referring to a marker placed on the sacrum [22]. In addition, the kinetic and kinematic parameters of the leading limb were analyzed during each phase. For the walking trial data, only Phases 1 and 2 were analyzed because data from Phase 3 could not be obtained.

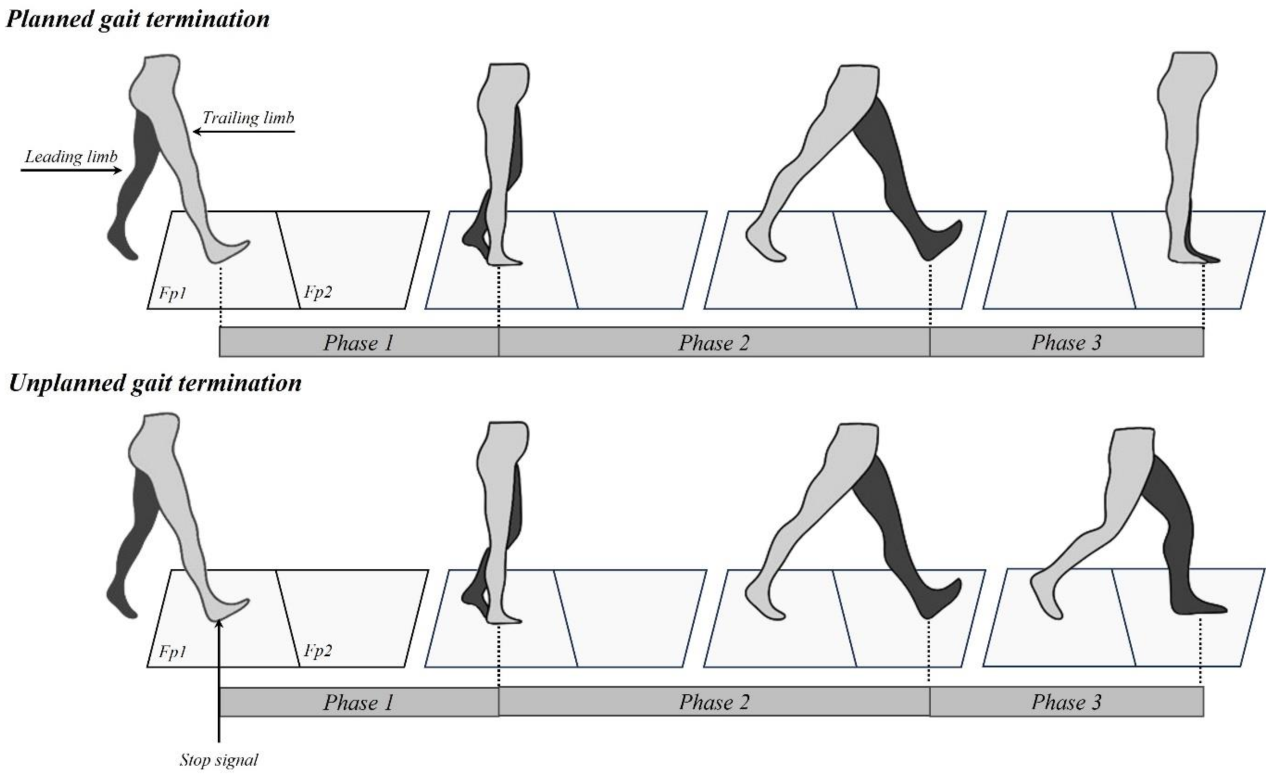

Figure 2. Phase of planned and unplanned gait terminations.

2.2.5. Statistical Analysis

Statistical analysis was performed using SPSS software (version 21.0; SPSS Inc., Chicago, IL, USA). The Shapiro–Wilk test was used to assess the normality of the outcome measures. Descriptive statistics were computed for all the demographic and outcome measures. The independent variables were the gait conditions (walking, PGT, and UGT). The dependent variables were the spatiotemporal (gait velocity, stride length, normalized stride length, GT time, and GT step length), kinematic (ROM of the hip, knee, and ankle joints), and kinetic (peak GRF-y and GRF-y impulses) data. The non-parametric Friedman test was used to analyze differences in kinematic and spatiotemporal data, excluding GT time and GT step length between conditions. Bonferroni-adjusted post hoc Wilcoxon signed-rank tests were used to compare individual pairs of conditions, and a *p*-value of less than 0.017 was considered statistically significant [23]. The Wilcoxon signed-rank test was used to analyze the differences in kinematic, kinetic, and spatiotemporal data (GT time and GT step length) between the PGT and UGT conditions. Statistical significance was set at $p < 0.05$.

3. Results

Table 1 shows the spatiotemporal data according to the walking, PGT, and UGT conditions. There were no significant differences in the gait velocity, stride length, and normalized stride length between the conditions ($p > 0.05$). The GT time and GT step length were significantly different between PGT and UGT ($p < 0.05$).

Table 1. Comparison of spatiotemporal data between gait conditions.

	Walking	PGT	UGT	*p*-Value
Stride length (m)	1.27 ± 0.12	1.25 ± 0.09	1.28 ± 0.12	0.350
Normalized stride length (ratio)	1.47 ± 0.10	1.45 ± 0.11	1.48 ± 0.10	0.350
Gait velocity (m/s)	1.16 ± 0.12	1.11 ± 0.10	1.14 ± 0.12	0.076
GT time (s)	-	0.86 ± 0.10	0.58 ± 0.14	<0.001 *
GT step length (m)	-	0.59 ± 0.05	0.66 ± 0.07	0.002 *

GT, gait termination; alking, walking trial; PGT, planned gait termination trial; UGT, unplanned gait termination trial; GRF, ground reaction force; * $p < 0.05$.

In Phase 1, there were no significant differences in the hip and knee ROM between the conditions ($p > 0.05$), but there was a significant difference in the ankle ROM ($p < 0.05$) (Table 2). The results of the post hoc analysis showed that the ankle ROM of the PGT was slightly lower than that of the UGT ($p < 0.017$). As shown in Table 2, there were significant differences in the hip, knee, and ankle ROM between the conditions in Phase 2 ($p < 0.05$). The hip ROM was slightly greater during walking than during PGT. The knee ROM in the UGT was slightly greater than that in PGT. The ankle ROM in walking was slightly lower than in PGT and UGT ($p < 0.017$). Table 2 shows the kinematic and kinetic parameters in Phase 3 during the PGT and UGT. Compared to PGT, hip ROM was significantly lower, but knee ROM was significantly greater in UGT ($p < 0.05$) (Figure 3). In addition, all kinetic parameters in UGT were significantly greater than those in PGT ($p < 0.05$). However, there was no significant difference in the ankle angle between PGT and UGT ($p > 0.05$).

Table 2. Comparison of kinematic and kinetic parameters across different gait conditions.

			Walking	PGT	UGT	*p*-Value	Post Hoc
ROM (°)	Phase 1	Hip joint	36.23 ± 4.22	36.64 ± 2.57	36.21 ± 4.01	0.638	
		Knee joint	48.86 ± 4.99	48.62 ± 5.61	49.90 ± 4.59	0.387	
		Ankle joint	29.41 ± 5.41	27.35 ± 4.96	29.71 ± 4.12	0.032 *	b < c
	Phase 2	Hip joint	5.48 ± 0.91	4.15 ± 1.36	4.73 ± 1.37	0.006 *	a > b
		Knee joint	52.77 ± 5.51	48.57 ± 7.62	54.50 ± 4.63	0.004 *	b < c
		Ankle joint	7.05 ± 4.82	8.44 ± 5.40	8.80 ± 4.38	0.001 *	a < b, c
	Phase 3	Hip joint	-	23.30 ± 3.33	10.07 ± 3.97	<0.001 *	
		Knee joint	-	10.66 ± 6.55	14.28 ± 6.78	0.010 *	
		Ankle joint	-	14.09 ± 4.62	14.38 ± 2.80	0.217	
GRF (N/kg)		Peak GRF	-	0.21 ± 0.05	0.34 ± 0.08	<0.001 *	
		GRF impulse	-	0.08 ± 0.02	0.09 ± 0.02	<0.001 *	

ROM, range of motion; GRF, ground reaction force; walking, walking trial; PGT, planned gait termination trial; UGT, unplanned gait termination trial; * $p < 0.05$.

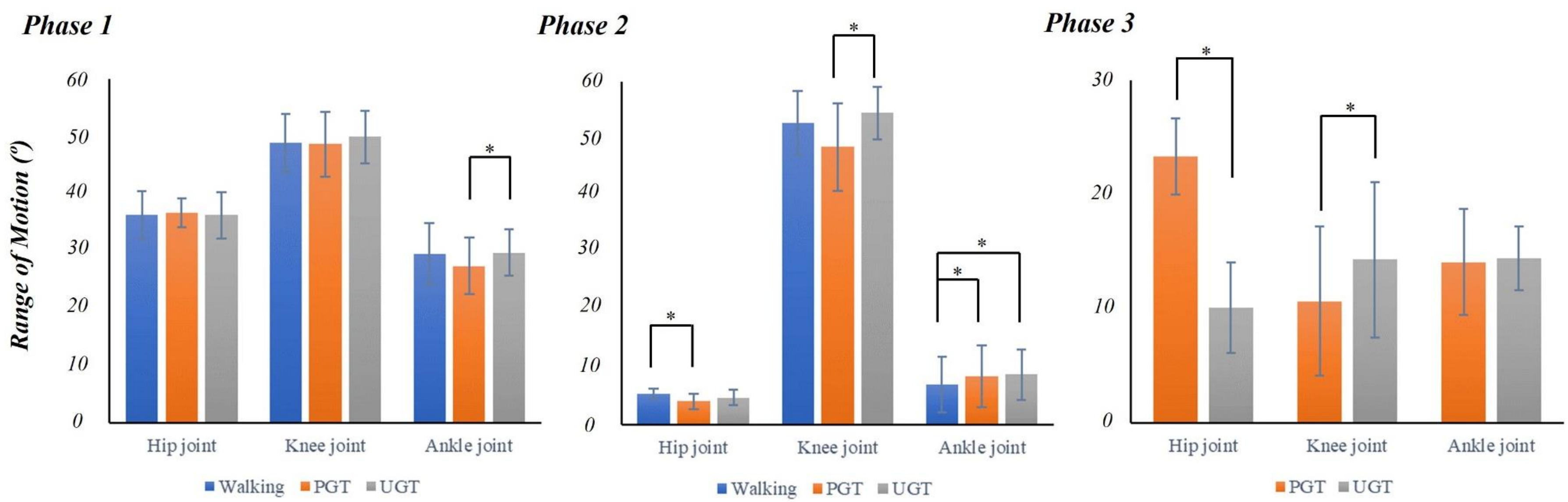

Figure 3. Comparison of joint range of motion between the walking and gait termination trials across phases. Walking, walking trial; PGT, planned gait termination; UGT, unplanned gait termination. * Significant difference in range of motion between conditions ($p < 0.05$).

4. Discussion

The purpose of this study was to investigate the spatiotemporal, kinematic, and kinetic parameters of the leading limb during walking, PGT, and UGT to comprehend the mechanism that prepares and generates the braking force during the pre-stopping, initial stopping, and terminal stopping phases. Our results showed that both planned and unplanned stopping were similar to usual walking in terms of the spatiotemporal parameters. An exception to this occurred between PGT and UGT. In our results, the GT time during the PGT trial was greater than that during the UGT trial, which may be due to the pre-informed foot positioning of where to stop in the PGT trial [10,24]. The subjects were asked to stop with their feet parallel to a designated force plate during the PGT trial. However, it was rare to keep the feet parallel in the UGT trial. A previous study has shown that planned stopping takes approximately 0.5s longer than unplanned stopping because of the additional time required to place the feet parallel [24]. However, in our study, the GT step length during UGT was greater than that during PGT. This difference may be attributed to the effective control of the COM to acquire dynamic stability during the PGT and UGT trials. In a previous study, when gait was terminated due to an unexpected stimulus, the body absorbed the sudden increase in the GRF and showed gait termination with a long stride length as a reaction to control the movement of the COM [25]. Therefore, it is thought that the braking force was applied by increasing the stride length to stop while maintaining stability in response to the unexpected stop signal because of the lack of a pre-informed stopping point in the UGT condition in our study.

In this study, we subdivided gait termination into three phases based on previous studies to compare the differences in kinematic and kinetic parameters between gait conditions [2,26,27]. Phase 1 consisted of the last stride prior to stopping, from heel contact of the trailing limb to maximal advancement of the mid-stance, where propulsive force occurs in stance phases. In this phase, the leading limb enters the pre-swing, initial swing, and mid-swing phases, which involve lifting the foot off the ground, moving forward, and accelerating the swing [28]. The swing limb is not only rapidly accelerated forward by ankle plantar flexion during the pre-swing to generate propulsive force but also rapidly accelerated forward by ankle dorsiflexion during the initial swing, increasing the angular velocity to advance [28,29]. During Phase 1, there were no significant differences in the hip and knee ROM between the gait conditions, except for the ankle ROM. In addition, the ankle ROM was significantly lower in the PGT trial than in the UGT trial. These results can be explained by the decrease in propulsive force at gait termination in response to a stop signal [18,30]. According to the reported literature, for this time, a 10% reduction in gait velocity was observed in the PGT trial, and the period of generating propulsive force was reduced compared with walking. In the PGT condition, participants exhibited lower peak plantar flexion during pre-swing and less dorsiflexion after toe-off, compared to the UGT condition [31]. This strategy decelerates advancement by decreasing dorsiflexion during the swing phase [32,33]. Therefore, in the PGT condition, the ankle joint is considered to predominantly contribute to deceleration in the initial preparation for generating the braking force [32,33]. In contrast, in the UGT condition, the subjects had to respond to an unexpected stop signal during Phase 1. When unexpected stimulation forces the body to stop walking suddenly, dynamic stability is disrupted because it does not have enough response processes [34,35]. Subsequently, the ankle joint during this period would not be successful in generating braking forces owing to instability and disturbing kinesthetic control [19,34,35].

Phase 2 is a major braking phase that reduces gait velocity by 60–70% and includes the terminal swing of the leading limb [36]. Previous studies have emphasized the importance of rapid variability in ankle joints and control of plantar flexion moment for generating braking force [37,38]. Our results were consistent with those of a previous study, which showed greater ankle ROM during both PGT and UGT, compared to walking [4,39]. In addition, greater knee ROM was observed in UGT than in the PGT [4]. Previous studies have reported that the hip and knee strategy that absorbs forces and controls the movement of the COM is preferred to complete gait termination safely and quickly in response to an unexpected stimulus. Greater hip and knee flexion allow subjects to increase the braking force faster to reach a COM stop [25,32,40]. Previous findings suggest that hip and knee kinematic information is the primary variable of interest in gait termination [4,25]. However, in our results, a lower hip ROM was observed during PGT than during walking, which is thought to be associated with a shorter step length in PGT because the gait velocity was similar between the three conditions. In addition, step length positively correlated with hip ROM [41]. For example, during the PGT trial, most subjects landed posteriorly in both walking and UGT foot positions, resulting in shorter step lengths. Perhaps subjects in the PGT trial prepared for deceleration by relying on the ankle joint rather than the hip and knee joints to absorb force and control the COM motion in the terminal swing.

In Phase 3, differences in joint motion between PGT and UGT were investigated to elucidate the mechanisms underlying body stability during gait termination. The results showed that the UGT trial exhibited a significantly lower hip ROM and significantly greater knee ROM than the PGT trial. The COM during UGT is moved backward to stretch the hip joint, and knee flexion is increased to stably convert forward inertia [8]. However, ankle ROM did not show a statistically significant difference between the PGT and UGT trials. This may be because the body primarily focuses on stabilization and the ankle joint is not actively involved in generating the braking force. These findings suggest that during PGT, gait can be terminated while gradually maintaining the stability of the whole body through external rotation of the hip joint and slight flexion of the knee joint [32,42,43].

From the perspective of ground reaction forces (GRF) occurring in Phase 3, when an individual suddenly stops their gait (i.e., during UGT), both vertical and anteroposterior (A-P) GRF increase abruptly. This is because of the need to counter the body's forward momentum, which generates significant rearward stimuli [40,44]. In addition, the vertical impulse increases to provide support to the body during deceleration [45]. The magnitude of the GRF varies according to an individual's velocity, mass, deceleration duration, and extent [45]. In this study, we observed no significant differences in the velocity and mass of the subjects, implying that the differences in the GRF magnitude arise from the characteristics of the push-off and unloading phases of gait. Our findings suggest that the unloading phase can rapidly adjust the GRF to counteract forward momentum and maintain equilibrium.

This study has several limitations. First, the study was conducted on healthy young adults; therefore, the findings may not be generalizable to other populations with gait impairment. Second, the study only focused on spatiotemporal, kinematic, and kinetic parameters and did not consider other factors that may affect gait termination, such as cognitive and neurological factors. In addition, the study only investigated gait termination on level ground and did not consider gait termination on inclines or declines. Finally, this study only investigated gait termination at one designated force plate during PGT, which may limit the generalizability of the findings to other stopping locations.

5. Conclusions

In conclusion, this study found that, in the context of gait termination, the ankle joint plays a predominant role in decelerating the body during the initial preparation for generating braking force in the PGT condition. Conversely, in the UGT condition, instability of the ankle joint disrupts kinesthetic control and hinders the generation of braking forces. Consequently, a strategy that involves the hip and knee, focusing on force absorption and control of the center of mass, is preferred for safe and rapid gait termination in response to unexpected stimuli. These findings provide valuable insights into the biomechanical mechanisms underlying body stability during walking cessation and may facilitate the development of more effective rehabilitation strategies for individuals with walking impairments.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Dankook University (DKU 2021-03-062).

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

Data Availability Statement: The data presented in this study are available from the corresponding author upon request.

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

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