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Kinematic synergy of speed reduction during stair descent

JUN NAKAMURA[1], REO IGURA[2], MASAYA ANAN[1]*

[1] Physical Therapy Course, Faculty of Welfare and Health Science, Oita University, Japan.
[2] Hiroshima University Hospital, Japan.

Purpose: This study aimed to quantify multi-segmental coordination using Uncontrolled Manifold (UCM) analysis to examine the effect of speed reduction on the control of stair descent. *Methods*: Twenty healthy participants performed stair descent at a self-comfortable pace for normal speed conditions and at a slow speed set to a metronome rhythm of 60 beats/min. UCM analysis was separately conducted for the center of mass (COM) and swing foot, with anteroposterior and vertical movements designated as task variables, and segment angles defined as elemental variables. ΔV, the normalized difference between the variance in segment angle that does not affect task performance (V_{UCM}) and the variance that does affect task performance (V_{ORT}) was calculated separately for the COM and swing foot and compared between normal and slow speeds. *Results*: The V_{ORT} for the COM and the swing foot in the anteroposterior direction were significantly lower at slow speeds than at normal speeds. The V_{ORT} of task-relevant segment angles affecting COM control in the vertical direction was significantly higher at slow speed compared to normal speed. Additionally, the ΔV in segment angle variance impacting swing foot control in the anteroposterior direction was significantly greater at slow speed than at normal speed. *Conclusions*: The findings suggest that descending stairs at reduced speed promotes enhanced coordination of lower limb segments for controlling the swing foot in the anteroposterior direction, while concurrently increasing segmental variability that destabilizes the vertical COM.

Key words: *coordination, speed, variance, uncontrolled manifold, stair, descent*

1. Introduction

Stair descent represents a fundamental aspect of daily living, essential for navigating both indoor and outdoor environments. However, it ranks among the top five challenging activities for elderly adults aged 60 years or older, influenced by various factors [20]. This challenge extends beyond the elderly population, affecting individuals with degenerative lower limb joint diseases and balance disorders [19].

Stair descent requires increased joint movements and joint moments compared to level walking [12], [13]. Thus, various studies have investigated the factors that cause difficulties in descending stairs using kinetic and kinematic variables. Older adults are reported to have more difficulty descending than younger adults owing to the decreased eccentric contraction force of the ankle plantar flexor muscles and decreased knee joint flexion angle [4]. The margin of stability, which is the extrapolated center of mass (COM) position that considers the position and speed of the COM, has also been utilized in stair descent as an index to evaluate dynamic stability [6]. Thus, changes in the individual muscles and joint angles of the lower limbs during stair descent and COM stability have been reported in previous studies.

However, the human body is composed of many muscles and joints that are controlled in a coordinated manner to stably perform tasks. Therefore, evaluating tasks from the perspective of the coordination of each element is necessary. Recently, a method called the uncontrolled manifold (UCM) analysis has been applied in motion analysis research to evaluate the coordination of body movements [8]. The task variable is

* Corresponding author: Masaya Anan, Physical Therapy Course, Faculty of Welfare and Health Science, Oita University, Japan. E-mail: anan-masaya@oita-u.ac.jp

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the goal of accomplishing the task, that is, the most important variable in the task, and the element variables are the elements that control the task variable. In stair descent, control of two tasks is required: moving the COM forward and downward and contacting the swing foot on the tread of a stair. The combination of segment angles throughout the body that control these movements and are structured to achieve the objective is referred to as "synergy". This synergy can be evaluated using UCM analysis. UCM analysis has been used in previous studies using individual factors, e.g., in older adults [2], [7] and stroke patients [11]. Moreover, environmental factors, such as narrow paths [16] and irregular surfaces [3] have been reported to influence the coordination between segments of the whole body. Because stair descent requires similar adaptation to the external environment of the stairs, it is important to evaluate coordination using UCM analysis. In addition, stair descent has been reported to decrease speed and prolong single-support time in the elderly and in those with functional limitations [4], [5]. Different stair-descending speeds are expected to alter muscle activity patterns and joint movements, which subsequently affect the coordination between segments of the entire body to control the task.

This study aimed to investigate the effect of speed reduction on stair descent control by quantifying the coordination of joint movements necessary to accomplish the task of descending stairs in healthy young subjects, using UCM analysis. We hypothesized that descending stairs at reduced speed would increase the coordination of joint movements in the anteroposterior direction because it is necessary to pay attention to the appropriate contact of the swing foot on the tread surface.

2. Materials and methods

2.1. Participants

The participants were 20 healthy young adults (10 males and 10 females). Their age, height and mass were 21.6 ± 1.1 years, 1.65 ± 0.10 m and 57.4 ± 10.3 kg, respectively. The participants had no previous or current history of orthopedic diseases of the lower extremities or lumbar region. The purpose of the study was explained to the subjects before measurement, and a consent form was signed. Prior to the measurements, the research plan was approved by the Ethics Committee of the Faculty of Welfare and Health Science, Oita University (approval number: F210033).

2.2. Apparatus and experimental procedure

Kinematic data were acquired at a sampling rate of 100 Hz using 10 infrared cameras and a Vicon 3D motion analysis system (VICON, Oxford, UK) with infrared reflective markers. This system uses infrared cameras to recognize infrared reflection markers in gait laboratories. Kinetic data were acquired using eight force plates (AMTI, MA, USA) at a sampling rate of 1000 Hz. Forty-nine infrared reflective markers (14 mm in diameter) were attached to the following anatomical landmarks on the anterolateral head, posterolateral head, superior anterior iliac spine, superior posterior iliac spine, iliac crest, acromion, lateral humeral epicondyle, medial humeral epicondyle, radial styloid process, ulnar styloid process, second metacarpal, femoral greater trochanter, femoral lateral epicondyle, femoral medial epicondyle, tibial lateral epicondyle, tibial medial epicondyle, external and internal tubercles, fifth metatarsal, first metatarsal and calcaneus. The bones were identified as the sternal scapes, xiphoid process, seventh cervical spinous process, second thoracic spinous process, tenth thoracic spinous process, twelfth thoracic spinous process, and fourth lumbar spinous process on the right and left sides.

The experimental staircase consisted of four steps (step height of 17.0 cm, tread length of 30.0 cm). Because the step length during stair descent was determined by the stair tread, the change in cadence was directly related to the change in speed. The normal condition was performed at the participants' comfortable speed, while the slow condition was performed with the cadence set to 60 steps/min using a metronome. Before each measurement, the participants practiced the task sufficiently. The participants descended stairs barefoot in a step-over-step manner.

2.3. Data processing

Data analysis was performed using the BodyBuilder software (Vicon, Oxford, UK). The kinematic and kinetic data obtained were low-pass filtered using a Butterworth filter, with marker coordinates filtered at 6 Hz and floor reaction forces at 20 Hz. Nine rigid-body link models were created from the marker coordinates obtained for the head, thorax, pelvis, thighs, shanks and feet, and the global and local coordinate systems were defined. COM coordinates were calculated based on the inertial properties of the body segments [10]. The first step of descending stairs was performed using the right lower limb, and the two left-swing phases were analyzed. The swing phase was defined as when the vertical vector of the floor reaction was below 10 N. Each condition was measured 10 times, and a total of 20 left-leg swing phase data were obtained. The mean values of COM speed in the direction of travel, vertical direction, and cadence during stair descent were calculated.

UCM analysis was conducted using MATLAB R2018a (MathWorks, Tokyo, Japan) to evaluate the coordination between the segments controlling the COM and swing foot during stair descent. For the UCM analysis, we employed a step count of 20 for each participant. Rosenblatt et al. [15] recommend this number as sufficient to obtain a valid index. The anteroposterior (COM_y) and vertical (COM_z) directions of the COM and the anteroposterior (ANK_y) and vertical (ANK_z) directions of the swing foot were set as task variables, and geometric models of the element variables associated with them were created [16], [21]. The relationship between the trajectories of the task variables and element variables was estimated using the Jacobian (J), which is the matrix of partial derivatives of the task variables for each segment angle variable. ε, the null space of J, is a basis vector over the linearized UCM that is computed to provide the null space has $n-d$ vectors spanning the UCM (ε_1, ε_2, ..., ε_{n-d}), where n is the number of dimensions of the segment configuration space and d is the number of dimensions of the task variable. The difference of each trial from the mean in the segment angle space ($\theta-\bar{\theta}$) projected onto ε_i is Θ_{UCM}, and the projection onto a vector orthogonal to ε_i is Θ_{ORT}. V_{UCM} and V_{ORT} were calculated using the following equations [16], [17].

$$\Theta_{UCM}=\sum_{i=1}^{n-d}(\theta-\bar{\theta})\times\varepsilon_i\ , \tag{1}$$

$$\Theta_{ORT}=(\theta-\bar{\theta})-\Theta_{UCM}\ , \tag{2}$$

$$V_{UCM}=\sqrt{(n-d)^{-1}\times N^{-1}\times\Sigma(\Theta_{UCM})^2} \tag{3}$$

$$V_{ORT}=\sqrt{d^{-1}\times N^{-1}\times\Sigma(\Theta_{ORT})^2}\ . \tag{4}$$

In the case of $V_{UCM} > V_{ORT}$, synergy exists in the segment angle variations, and their combination does not affect the stability of the position of the task variable. However, when $V_{UCM} < V_{ORT}$, there is no synergy, indicating that the combination of segment angle variations causes the task variable to deviate from its stable position. The strength of synergy was calculated using the synergy index ΔV defined by the following equation [14], [18].

$$\Delta V=\frac{V_{UCM}-V_{ORT}}{V_{TOT}} \tag{5}$$

V_{UCM}, V_{ORT}, ΔV were divided into the first half (0–50%) and the second half (51–100%) of the swing phase, and the mean value of each was adopted. The variance components (V_{UCM}, V_{ORT}) were always positive, but ΔV was not normally distributed because it varied from positive to negative. Therefore, to solve this problem and apply statistical analysis, ΔV was log-transformed using Fisher's z-transform.

2.4. Statical analysis

Statistical analysis was performed using SPSS Statistics23 (IBM Japan, Tokyo, Japan). The normality of the data distribution was checked using the Shapiro–Wilk test. Two-way ANOVA was performed including within-subject factors for the variance components (V_{UCM}, V_{ORT}) and the speed condition (normal, slow). The significant main effect of the variance component ($V_{UCM} > V_{ORT}$) indicated the presence of synergy. In addition, a paired t-test was performed to compare COM speed, cadence and ΔV between the two conditions. The effect size used the η_p^2. The significance level was set at 5%.

3. Results

In Table 1, the measured COM speed and cadence while descending the stairs are listed. Cadence was significantly lower during the slow condition ($p < 0.001$).

The UCM indices for the COM are listed in Table 2. ANOVA revealed significant effects of variance components during the swing phase of the COM. Specifically, significant effects were observed in the first half of the swing phase in the anteroposterior direction ($p < 0.001$), first half of the swing phase in the vertical direction ($p < 0.001$), and second half of the swing phase in the vertical direction ($p = 0.002$). These results indicate the presence of synergy ($V_{UCM} > V_{ORT}$). In the anteroposterior direction of COM, V_{UCM} ($p = 0.782$), V_{ORT} ($p = 0.325$) and ΔV ($p = 0.250$) were not significantly different between conditions in the first half of the swing phase. In the second half of the swing phase, V_{UCM} ($p = 0.073$) and ΔV ($p = 0.242$) were not significantly different between conditions, and V_{ORT} was significantly lower during the slow condition ($p = 0.030$). In vertical COM, V_{UCM} ($p = 0.798$), V_{ORT} ($p = 0.941$) and ΔV ($p = 0.239$) were not sig-

Table 1. Gait parameters

	Normal	Slow	P-value	Effect size	Power
COM anteroposterior speed [m/s]	0.47(0.04)	0.3(0.02)	<0.000*	0.855	1.000
COM vertical speed [m/s]	–0.24(0.03)	–0.18(0.03)	<0.000*	0.611	1.000
Cadence [steps/min]	105.3(26.2)	63.8 (3.57)	<0.000*	0.564	1.000

Mean (SD), * $p < 0.05$.

Table 2. UCM indices of COM

	Normal	Slow	P-value	Effect size	Power
First half					
Anteroposterior ΔV	0.59 (0.09)	0.62 (0.09)	0.250	0.002	0.058
V_{UCM} [$\times 10^{-3}$ rad^2]	2.4 (1.3)	2.5 (1.4)	0.782	0.077	0.058
V_{ORT} [$\times 10^{-3}$ rad^2]	1.2 (0.4)	1.1 (0.5)	0.325	0.391	0.091
			< 0.001†	0.704	1.000
Vertical ΔV	0.54 (0.11)	0.58 (0.09)	0.239	0.036	0.215
V_{UCM} [$\times 10^{-3}$ rad^2]	2.4 (1.3)	2.4 (1.3)	0.798	0.004	0.057
V_{ORT} [$\times 10^{-3}$ rad^2]	1.6 (0.7)	1.5 (1.4)	0.941	0.000	0.051
			< 0.001†	0.435	0.952
Second half					
Anteroposterior ΔV	0.48 (0.11)	0.53 (0.13)	0.242	0.013	0.106
V_{UCM} [$\times 10^{-3}$ rad^2]	2.4 (1.3)	1.9(1.1)	0.073	0.159	0.437
V_{ORT} [$\times 10^{-3}$ rad^2]	1.9 (0.9)	1.4 (0.8)	0.030*	0.225	0.606
			0.073	0.159	0.436
Vertical ΔV	0.57(0.12)	0.50 (0.10)	0.053	0.095	0.495
V_{UCM} [$\times 10^{-3}$ rad^2]	2.2 (1.0)	1.9 (1.2)	0.123	0.120	0.335
V_{ORT} [$\times 10^{-3}$ rad^2]	1.1 (0.5)	1.7 (0.9)	0.008*	0.314	0.799
			0.002†	0.372	0.889

Mean (SD), * $p < 0.05$ Normal vs. Slow, † $p < 0.05$ V_{UCM} vs. V_{ORT}.

Table 3. UCM indices of swinging foot

	Normal	Slow	P-value	Effect size	Power
First half					
Anteroposterior ΔV	0.31(0.08)	0.32(0.10)	0.600	0.011	0.099
V_{UCM} [$\times 10^{-3}$ rad^2]	1.9 (0.9)	2.3 (1.5)	0.292	0.058	0.177
V_{ORT} [$\times 10^{-3}$ rad^2]	2.5 (1.4)	2.4 (1.0)	0.798	0.004	0.057
			0.100	0.136	0.374
Vertical ΔV	0.34 (0.06)	0.35 (0.07)	0.714	0.004	0.066
V_{UCM} [$\times 10^{-3}$ rad^2]	1.9 (0.9)	2.2 (1.1)	0.295	0.063	0.189
V_{ORT} [$\times 10^{-3}$ rad^2]	2.5 (1.5)	2.9 (2.7)	0.517	0.024	0.101
			0.004†	0.361	0.875
Second half					
Anteroposterior ΔV	0.36 (0.10)	0.42 (0.08)	0.024*	0.039	0.227
V_{UCM} [$\times 10^{-3}$ rad^2]	1.8 (0.6)	1.7 (0.9)	0.502	0.024	0.100
V_{ORT} [$\times 10^{-3}$ rad^2]	1.8 (0.8)	1.2 (0.5)	0.005*	0.345	0.851
			0.115	0.126	0.348
Vertical ΔV	0.43 (0.07)	0.39 (0.08)	0.090	0.044	0.251
V_{UCM} [$\times 10^{-3}$ rad^2]	1.9 (0.6)	1.5 (0.7)	0.168	0.098	0.275
V_{ORT} [$\times 10^{-3}$ rad^2]	1.5 (0.7)	1.4 (0.7)	0.732	0.006	0.063
			0.002†	0.394	0.148

Mean (SD), * $p < 0.05$ Normal vs. Slow, † $p < 0.05$ V_{UCM} vs. V_{ORT}.

nificantly different between conditions during the first half of the swing phase. In the second half of the swing phase, V_{UCM} (p = 0.123) and ΔV (p = 0.053) did not differ significantly between conditions, and V_{ORT} was significantly higher in the slow condition (p = 0.008).

The results of the UCM indices for the swinging foot are listed in Table 3. ANOVA revealed significant effects of variance components in the second half of the swing phase of the swing foot in the vertical direction (p = 0.002), indicating the presence of synergy ($V_{UCM} > V_{ORT}$). In the anteroposterior direction of the swing foot, V_{UCM} (p = 0.293), V_{ORT} (p = 0.798), and ΔV (p = 0.600) did not differ significantly between conditions in the first half of the swing phase. In the second half of the swing phase, V_{ORT} was significantly lower (p = 0.005) and ΔV significantly higher (p = 0.024) during the slow condition. In the vertical swing phase, V_{UCM}, V_{ORT}, and ΔV did not differ significantly between conditions throughout the swing phase.

4. Discussion

In this study, we investigated the effects of decreasing speed on stair descent control by quantifying the coordination of segment movements required to descend stairs using UCM analysis. The results revealed that descending stairs at reduced speed required more coordination of the lower limb segments to control the traveling directional swing leg, whereas segment angles attempted to destabilize the vertical COM.

Both the COM speed and cadence during stair descent were lower for the Slow condition compared to those during the Normal condition, and the COM speed and cadence during the Normal condition exhibited the same trend as those in a previous study conducted at a comfortable speed [9]. In this study, the descending step movement under slow conditions was performed in accordance with a metronome set at 60 steps/min, and the speed and cadence were significantly lower than those under Normal conditions.

During the Slow condition, the V_{ORT} of the vertical COM was higher in the latter half of the swing phase than that during the normal condition. This implies that the descending motion at reduced speed increased the trial-to-trial variability of the segment angle, which destabilized the COM for the downward descending task and indicates that coordinated control was compromised. A study using a walking task reported that simultaneous contraction of the periarticular muscles of the knee joint increased with decreasing speed [1]. In addition, a study using UCM analysis revealed that as the simultaneous contraction of muscles increases, the variability that destabilizes the vertical posture increases [21]. These findings suggest that the trial-to--trial variability of segmental angles that destabilize the vertical COM increases during stair descent at reduced speed.

During the slow condition, the V_{ORT} of the traveling directional swing foot showed a lower value and ΔV showed a higher value in the latter half of the swing phase compared to the Normal condition. During the Slow condition, V_{ORT} of the traveling leg was lower and ΔV was higher than during the normal condition. This suggests that the descending motion at reduced speed exhibited less fluctuation in the segment angle, which destabilized the control of the traveling leg in the direction of motion, indicating cooperative control of the traveling leg. Although the COM and the swinging foot should be controlled simultaneously in gait, it has been considered that focusing on the control of one element can potentially may destabilize the control of the other [22]. Therefore, in the descending step movement with reduced speed, attention to increasing the coordination of the swing foot may have led to decreased coordination of the COM.

Decreased segmental coordination controlling the vertical COM has been associated with the risk of falls in the elderly [22]. Such careful descending motion with reduced speed has been observed in the elderly and in those with joint diseases. Therefore, treatment and patient guidance may be necessary to address the causes of the decrease in speed.

One limitation of this study is that because comparisons were made under reduced-speed conditions for healthy young subjects, it was not possible to observe direct results on motor control during stair descent in the elderly or those with diseases. Therefore, because we have only demonstrated basic findings regarding the decrease in movement speed with aging and disease, it is necessary to conduct future research on the elderly based on this study to demonstrate the changes in coordinated motor control during stair descent.

5. Conclusions

The findings of this study suggest that descending stairs at reduced speed promotes enhanced coordination of lower limb segments for controlling the swing foot in the anteroposterior direction, while concurrently increasing segmental variability that destabilizes the vertical COM.

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Compliance with ethical standards

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the author's institution (approval number: F210033). The purpose and objectives of this study were fully explained to the subjects, and their written consent was obtained.

Conflict of interest

The authors have no financial or proprietary interests in any material discussed in this article.

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