ICIC Express Letters
Part B: Applications
Volume **12**, Number **7**, July **2021**

ICIC International ©2021 ISSN 2185-2766
pp. **595–601**

AGE-RELATED CHANGES IN LEG CONTROL AT MINIMUM TOE CLEARANCE DURING WALKING

Yoshimitsu Hashizume[1], Shoko Kaichida[2], Kotaro Takeda[3] and Jun Nishii[4]

[1]Faculty of Management and Information Sciences
Kyushu Institute of Information Sciences
6-3-1, Saifu, Dazaifu, Fukuoka 818-0117, Japan
hashizume@kiis.ac.jp

[2]National Institute of Technology
Tokuyama College
Gakuendai, Shunan, Yamaguchi 745-8585, Japan
kaichida@tokuyama.ac.jp

[3]Faculty of Rehabilitation
School of Healthcare
Fujita Health University
1-98, Dengakugakubo, Kutsukake-cho, Toyoake, Aichi 470-1192, Japan
ktakeda@fujita-hu.ac.jp

[4]Graduate School of Science and Technology for Innovation
Yamaguchi University
1677-1, Yoshida, Yamaguchi City, Yamaguchi 753-8512, Japan
nishii@yamaguchi-u.ac.jp

Received November 2020; accepted February 2021

Abstract. *The variability of the minimum toe clearance (MTC) has been considered as a risk parameter for stumbling and falling, especially in elderly people. This study evaluates the hypothesis that MTC variability increases with age because the inter-joint synergy – suppressing the variability of the toe position relative to the hip position – deteriorates. We recorded the leg joint trajectories of six young and six old subjects during level walking, and the strength of joint synergies at the instant of MTC was evaluated based on uncontrolled manifold analysis. The results indicated that the variance of toe height from the ground was larger in the older group, although the joint synergies observed in both age groups exhibited no statistical difference. This fact suggested that the increase in the variability of the MTC might not result from the functional decline of inter-joint synergy but from the instability of the hip height.*
Keywords: Gait, Uncontrolled manifold, Joint synergy, Aging, Minimum toe clearance

1. **Introduction.** Bipedal walking requires precise coordination of whole-body movement to maintain body balance and generate propulsive force. In order to reveal the control mechanism, several recent studies have analyzed the inter-joint coordination (joint synergy) during walking by using the uncontrolled manifold (UCM) analysis [1]. According to the literature, leg joint synergy works so as to suppress the variability of the center of mass (COM) position during the stance phase [2] and step width [3, 4]. We also analyzed the leg joint synergy that stabilizes the toe position relative to the hip position in a walking stride by the UCM analysis. The results indicated that the joint synergy suppresses the variances of the hip position in the second double-support phase and the toe height at the instant of MTC, which is defined as the minimum vertical distance between the lowest point of the swing foot and the ground during the middle swing phase [5]. In general, the variability of the MTC has often been considered as a risk parameter

DOI: 10.24507/icicelb.12.07.595

that triggers stumbling, especially among older people [6, 7]. Therefore, the results of the current study signified that the formation of the joint synergy is an important control strategy to avoid stumbling.

Moreover, certain studies have investigated the influence of aging on such joint synergies during walking. For instance, the influence of age was not observed for the joint synergy that suppresses the variance of the step width and COM position [3, 8]; however, the joint synergies adjusting the step length were reported to decline among elderly people [8].

Mills et al. reported that older adults exhibited greater variance of the MTC as compared to younger adults [9]. Furthermore, several studies investigated the source of the variance of MTC and reported the relationship with the hip flexion-extension variability [10] as well as with the ankle dorsiflexion [11]. Nevertheless, the age-related variation in the leg joint synergy – regulating the foot height at the instant of MTC – has not been investigated. If MTC variability is due to diminished joint synergy, this implies the diminished nervous function that coordinates joint movements. Therefore, rehabilitation should be considered to improve this function for the elderly people. Hence, clarifying the effects of aging on joint synergy is important not only for understanding the mechanism of gait control but also for developing rehabilitation methods. In this paper, we examined whether the increasing variance of the MTC results from the joint synergy declining with age. In this paper, we examined whether the age-related increase in the variance of the MTC is due to the decline of the joint synergy or not.

2. Materials and Methods.

2.1. Participants.
Twelve healthy subjects participated in the experiment, including six females each in the older and younger age groups. The parameters of the subjects are listed in Table 1. The study was approved by the Ethics Committee of National Hospital Organization Murayama Medical Center, and all the subjects provided written informed consent regarding their participation. Moreover, the exclusion factors included being unable to walk without pain or the use of an assistive device, self-reporting of any falls, neuromusculoskeletal or other impairments that would alter performance, as determined from a physical examination.

Table 1. Parameters of each subject group

Variable	Older	Younger
Age (years)	72.2 (5.3)	19.4 (1.2)
Height (cm)	150.7 (6.8)	156.8 (4.5)
Weight (kg)	54.5 (9.6)	51.1 (7.1)

2.2. Apparatus and data acquisition.
The participants were equipped with reflective markers at the greater trochanter, knee, lateral malleolus, and fifth metatarsal, and they walked numerous times at a self-selected speed across a 7.5 m flat walkway. Typically, the subjects were allowed to rest when they experienced fatigue. While they walked through the walkway, the kinematics of the six older subjects were recorded using an infrared camera (MAC 3D System, Motion Analysis) at 120 fps and those of the younger subjects using a motion capture system (Himawari SP200, LIBRARY, Inc.) at 200 fps, for the central portion of the 3.5 m. Subsequently, the data were smoothed using a sixth-order low-pass Butterworth filter with a cutoff frequency of 6 Hz, and the N-stride data was extracted for each subject ($N = 30$, except for one older subject $N = 22$).

2.3. **UCM analysis.** The leg was modeled as a simple three-link system moving in the sagittal plane. The hip, knee, and ankle joint angles were defined by the angle between a vertical line and the thigh, crus, and foot, respectively. We examined joint synergies that suppressed the variance of horizontal and vertical toe positions, x and y, relative to the hip position at every instant during walking by the UCM analysis [1].

The leg posture at the instant of MTC was extracted, and the average joint angle $\overline{\boldsymbol{\theta}} = \left(\overline{\theta}_1, \overline{\theta}_2, \overline{\theta}_3\right)^T$ was computed for each subject, where $\overline{\theta}_i$ represents the average joint angle, and subscripts $i = 1$, 2, and 3 represent the hip, knee, and ankle, respectively. The distribution of the deviation of the joint angles

$$\boldsymbol{\sigma}^k = \boldsymbol{\theta}^k - \overline{\boldsymbol{\theta}} \tag{1}$$

was then analyzed using the UCM method, where $\boldsymbol{\theta}^k = \left(\theta_1^k, \theta_2^k, \theta_3^k\right)^T$ $(k = 1, 2, \ldots, N)$ is the joint trajectory of the k-th stride.

We summarize the procedure of the UCM analysis to evaluate the degree of the joint synergy that suppresses the toe height relative to the hip position. In this case, the manifold in the joint angle space on which the toe height takes the constant value $y(\boldsymbol{\theta}) = y\left(\overline{\boldsymbol{\theta}}\right)$ is called the uncontrolled manifold. The toe height is given by

$$y = -l_1 \cos\theta_1 - l_2 \cos\theta_2 - l_3 \cos\theta_3, \tag{2}$$

where l_i ($i = 1$, 2, and 3) represents the link lengths of the thigh, crus, and foot, respectively. The UCM upon which the toe height takes a constant value is two-dimensional and $\boldsymbol{\epsilon}_y^{\perp} = \nabla y(\boldsymbol{\theta})|_{\boldsymbol{\theta}=\bar{\boldsymbol{\theta}}}$ represents the orthogonal (ORT) direction to the UCM at $\boldsymbol{\theta} = \overline{\boldsymbol{\theta}}$. Furthermore, the UCM and ORT components of the deviation in the k-th stride $\boldsymbol{\sigma}_y^{k\parallel}$ and $\boldsymbol{\sigma}_y^{k\perp}$ can be expressed as

$$\begin{cases} \boldsymbol{\sigma}_y^{k\parallel} = \boldsymbol{\sigma}^k - \boldsymbol{\sigma}_y^{k\perp} \\ \boldsymbol{\sigma}_y^{k\perp} = \left(\boldsymbol{\sigma}^k \cdot \hat{\boldsymbol{\epsilon}}_y^{\perp}\right) \hat{\boldsymbol{\epsilon}}_y^{\perp}, \end{cases} \tag{3}$$

where $\hat{\boldsymbol{\epsilon}}_y^{\perp}$ is the unit vector in the direction of $\boldsymbol{\epsilon}_y^{\perp}$.

Therefore, the UCM and ORT components of variance, $V_y^{\parallel^2}$ and $V_y^{\perp^2}$, can be defined as

$$\begin{cases} V_y^{\parallel^2} = \dfrac{1}{Nd^{\parallel}} \displaystyle\sum_{k=1}^{N} \left|\boldsymbol{\sigma}_y^{k\parallel}\right|^2 \\ V_y^{\perp^2} = \dfrac{1}{N\left(d - d^{\parallel}\right)} \displaystyle\sum_{k=1}^{N} \left|\boldsymbol{\sigma}_y^{k\perp}\right|^2, \end{cases} \tag{4}$$

where $d = 3$ and $d^{\parallel} = 2$ are the dimensions of the joint angle space and the UCM, respectively. Therefore, $V_y^{\parallel^2}$ and $V_y^{\perp^2}$ are the variance components per degree of freedom in each joint subspace. When $V_y^{\parallel^2}$ is greater than $V_y^{\perp^2}$, i.e., the joint angle data distributes around the UCM rather than the ORT direction in the joint space, such a distribution suggests the existence of a joint synergy suppressing the toe height variance relative to the hip position.

The degree of synergy S_y can be defined as

$$S_y = \frac{V_y^{\parallel^2} - V_y^{\perp^2}}{V_y^{\parallel^2} + V_y^{\perp^2}}. \tag{5}$$

When all the data distributes on the UCM, we obtain $S_y = 1$. If there are sufficient large number of data, positive S_y indicates the existence of joint synergy that suppresses the data variability from the UCM.

In this study, we analyzed the variance of joint angle data by respecting two kinds of UCMs on which the vertical and horizontal toe position, y and x, are invariant, respectively. For this purpose, we computed the UCM components of joint variance $\left(V_x^{\|^2} \text{ and } V_y^{\|^2}\right)$, the ORT components $\left(V_x^{\perp^2} \text{ and } V_y^{\perp^2}\right)$, and the degrees of synergies (S_x and S_y) at the instant of MTC.

2.4. **Statistical analysis.** The differences in the degrees of synergies and variance components between the older and younger age groups were detected using the Welchs t-test, and the differences between the groups in the inter-subject variance were evaluated using the F-test. We also computed effect sizes by unbiased Cohen's d and the 95% confidence intervals (CIs) using Equations (14) and (17) in Nakagawa and Cuthill (2007) using R, respectively [12].

3. **Results.** The mean walking speeds of older and younger groups were 4.49 (1.05) km/h and 4.47 (0.47) km/h, respectively, with no statistical difference ($p = .963$, Cohen's $d = 0.03$, CI $[-1.11, 1.16]$).

Figure 1 depicts the degrees of joint synergies, S_x and S_y, which respectively suppresses the variance of the horizontal and vertical toe positions relative to the hip position at the instant of MTC. The horizontal dotted lines represent the threshold level above which $V_i^{\|^2}$ is greater than $V_i^{\perp^2}$ ($i \in \{x, y\}$) by the significance level $p = .05$ obtained from the F-test. In the computation of the level, we calculated the F-value by which the null hypothesis that two variance components $V^{\|^2}$ and $V^{\perp^2}$ are equal is rejected at $p < .05$, and obtained the value S that represents the threshold level by substituting the F-value for $V_i^{\|^2}/V_i^{\perp^2}$ in Equation (5). Figure 2 portrays (a) UCM components of variance $\left(V_x^{\|^2}, V_y^{\|^2}\right)$, and (b) ORT components $\left(V_x^{\perp^2}, V_y^{\perp^2}\right)$.

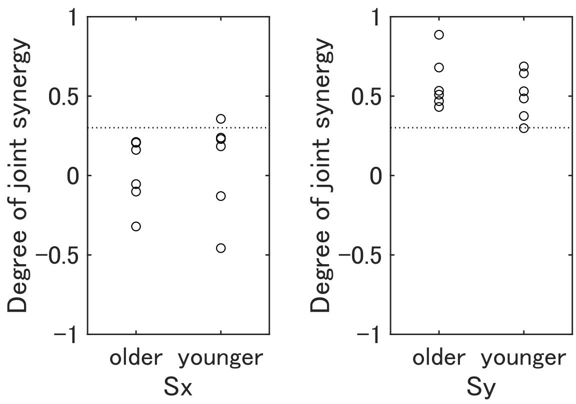


Figure 1. Degrees of joint synergies suppressing the variances of horizontal and vertical toe position relative to hip position, S_x (left) and S_y (right), respectively. The circles and horizontal dotted lines represent each subject data and the threshold level above which $V^{\|^2}$ is greater than $V^{\perp^2}$ under a significance level $p = .05$.

Furthermore, S_y was larger than the threshold level for all subjects, except one younger subject (Figure 1). However, the age groups did not exhibit statistically different results in terms of the mean values of synergies (S_x and S_y) and all the variance components $\left(V_x^{\|^2}, V_x^{\perp^2}, V_y^{\|^2} \text{ and } V_y^{\perp^2}\right)$ (Figures 1, 2, Table 2). By contrast, the inter-subject SDs of all the variance components, except $V_y^{\perp^2}$, demonstrated statistically significant increase in the older group (Figure 2, Table 2). These results show that no significant difference

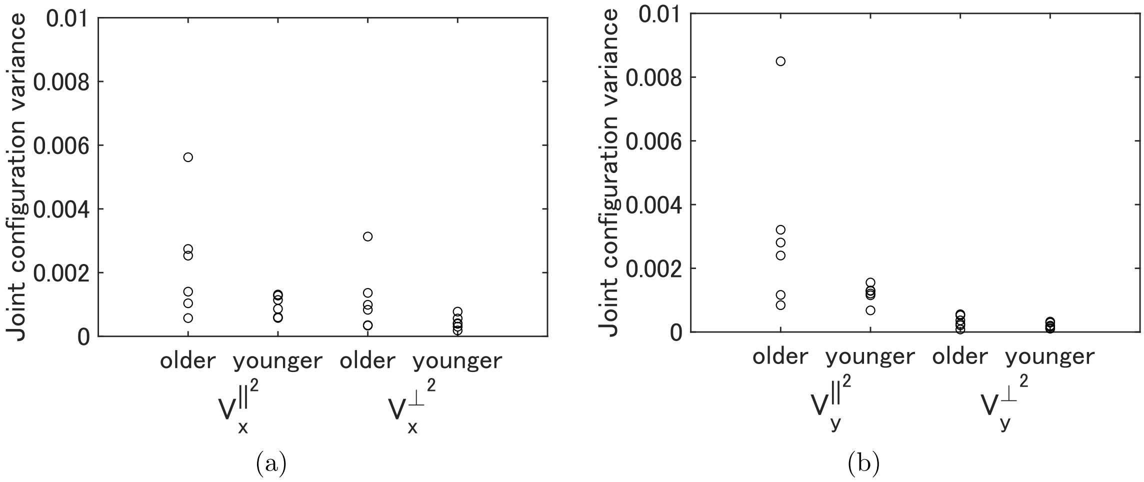


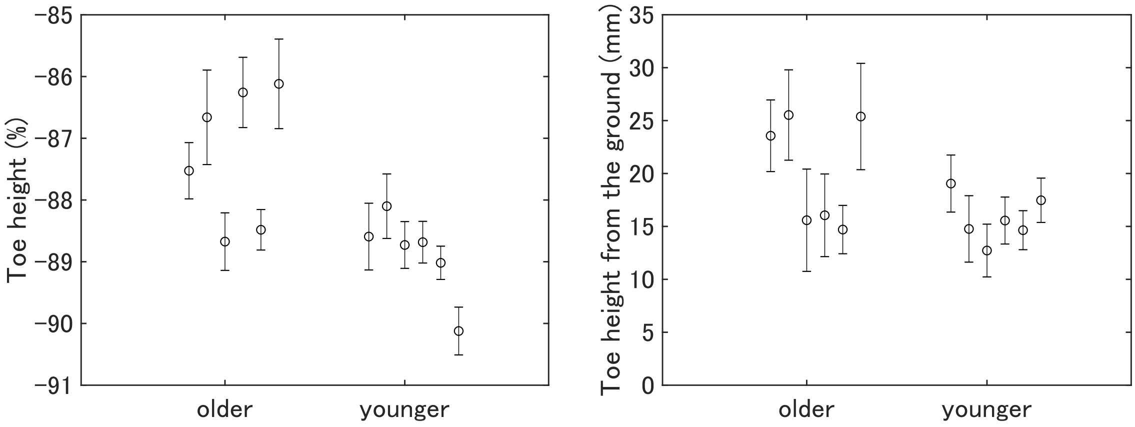
Figure 2. Variance components per degree of freedom. Subfigures (a) and (b) illustrate the variance components $V_x^{\|^2}$, $V_x^{\perp^2}$ and $V_y^{\|^2}$, $V_y^{\perp^2}$, respectively; the circles represent each subject data.

Table 2. Inter-subject means of the degree of joint synergies S_x and S_y and variance components $V_x^{\|^2}$, $V_y^{\|^2}$, $V_x^{\perp^2}$, $V_y^{\perp^2}$. ES = effect size (Cohen's d); CI = confidence interval. Standard deviations are in parenthesis. $^*p < .05$, $^{**}p < .01$.

Variable	Older	Younger	p (t-test)	ES	95%CI	p (F-test)
S_x	0.02 (0.20)	−0.07 (0.28)	.734	0.20	[−0.39, 0.29]	.449
S_y	0.59 (0.16)	0.50 (0.14)	.399	0.51	[−0.13, 0.29]	.789
$V_x^{\|^2}$ ($\times 10^{-3}$ rad^2)	2.32 (1.67)	0.96 (0.30)	.130	1.03	[−0.56, 3.27]	.002*
$V_x^{\perp^2}$ ($\times 10^{-3}$ rad^2)	1.17 (0.95)	0.44 (0.19)	.122	0.97	[−0.23, 1.69]	.003*
$V_y^{\|^2}$ ($\times 10^{-3}$ rad^2)	3.15 (2.53)	1.20 (0.26)	.117	0.99	[−0.58, 4.50]	.0001**
$V_y^{\perp^2}$ ($\times 10^{-3}$ rad^2)	0.33 (0.17)	0.20 (0.08)	.155	0.89	[−0.06, 0.32]	.142

in the degrees of the joint synergies at MTC was found in both age groups, and despite the increase in joint angle variance in the older group, the increase in the ORT variance component $V_y^{\perp^2}$ that affects the toe height was suppressed by the synergy.

Figure 3 portrays the toe height, and Table 3 presents the statistical data. The mean data and SDs of each subject are represented by the circles and error bar, respectively. In addition, two types of toe heights – from the hip position (Figure 3(a)) and from the ground (Figure 3(b)) – are shown, where the former toe height was normalized to the sum of inter-joint distances of the thigh, crus, and foot of each subject. In the latter, toe height was not normalized, and the ground height was defined as the lowest height of the toe in stance phase. Notably, the inter-subject mean of the toe height from the hip position was statistically higher in older subjects than those in the younger subjects; however, the inter-subject mean of the SDs between the age groups did not vary significantly, which is consistent with the previous result stating that the variability of the toe height is suppressed by the joint synergy. On the contrary, the inter-subject mean for the toe heights from the ground did not exhibit any statistical difference between the age groups. Notwithstanding, the inter-subject mean of the SDs for the older subjects was statistically larger than those of the younger subjects. Therefore, these results suggest that the increasing variability of the MTC would not result from the functional decline of inter-joint synergy in the swing leg but from the instability of the hip position.



(a) (b)

Figure 3. Toe height (a) relative to hip height and (b) from the ground. In the figures, the mean data and the SDs of each subject are represented by the circles and error bars, respectively. In subfigure (a), the data were normalized to the sum of inter-marker distances between thigh, crus, and foot of each subject.

Table 3. Inter-subject means of the mean toe height and standard deviation of each subject. Both the heights from hip and that from the ground were evaluated. In the former, the toe height was normalized to the sum of inter-marker distances of the thigh, crus, and foot for each subject. ES = effect size (Cohen's d); CI = confidence interval. Standard deviations are in parenthesis. $^{*}p < .05$, $^{**}p < .01$.

Toe height	Older	Younger	p	ES	95%CI
Mean (from hip, %)	−87.29 (1.12)	−88.87 (0.68)	.014*	1.72	$[0.40, 2.78]$
SD (from hip, %)	0.55 (0.17)	0.41 (0.11)	.104	1.03	$[-0.036, 0.33]$
Mean (from ground, mm)	20.14 (5.20)	15.70 (2.25)	.098	1.11	$[-1.07, 9.94]$
SD (from ground, mm)	3.95 (1.01)	2.41 (0.46)	.007**	1.95	$[0.52, 2.55]$

4. **Discussion.** The present study analyzed the leg joint angles of old and young adults at MTC during walking and compared the degrees of the leg joint synergies suppressing the variance of the horizontal and vertical toe position relative to the hip position. In both of the age groups, the leg joint synergies S_y displayed higher values than the threshold level, and no statistical differences were found in the degrees of joint synergies between the age groups. Moreover, the UCM hypothesis assumes that redundant degrees of freedom of our body are used for stabilizing the vital performance variables and accomplish a given task [1]. Thus, analyzing the abovementioned results based on this hypothesis, the toe height at the instant of MTC is an essential variable ensuring stable walking, which appears plausible as an increase in the toe height variance would trigger stumbling.

The variance of the toe height from the ground at MTC was statistically larger in older subjects than that in younger subjects, which is consistent with the report of Mills et al. [9]. However, the mean toe height from the hip position was statistically higher in older subjects than that in the younger subjects, which would reduce the chance of tripping. These results suggest that the increase of the MTC variability would not be caused by the functional decline of inter-limb joint synergy but by the instability of the hip height. Such instability could result from the declining control of the pelvis angle and inter-limb joint synergy, thus prompting clarification in future research.

5. **Conclusions.** In this study, we analyzed the leg joint synergy that stabilizes the toe position relative to the hip position at the instant of MTC during walking for both old and young subjects and found the following:

1) Despite the increase in variability of joint trajectory, the joint synergy stabilizing the relative toe height did not vary with age.
2) The variance of the MTC was statistically larger in older subjects than that in younger subjects. However, the mean toe height from the hip was statistically higher in the older group than that in the younger group.
3) The increased stumbling with age may be caused by the decline in the ability to control pelvis angle and inter-joint synergy rather than diminished inter-leg joint synergy.

Therefore, this study suggested that the training of pelvic or hip movement may be effective for maintaining gait stability among the elderly to prevent falling.

Acknowledgments. This work was supported by JSPS KAKENHI (Grant numbers 25282183, 19K19933).

REFERENCES

[1] J. P. Scholz and G. Schöner, The uncontrolled manifold concept: Identifying control variables for a functional task, *Experimental Brain Research*, vol.126, no.3, pp.289-306, 1999.
[2] E. Papi, P. J. Rowe and V. M. Pomeroy, Analysis of gait within the uncontrolled manifold hypothesis: Stabilisation of the centre of mass during gait, *Journal of Biomechanics*, vol.48, no.2, pp.324-331, 2014.
[3] V. Krishnan, N. J. Rosenblatt, M. L. Latash and M. D. Grabiner, The effects of age on stabilization of the mediolateral trajectory of the swing foot, *Gait & Posture*, vol.38, no.4, pp.923-928, 2013.
[4] N. J. Rosenblatt, C. P. Hurt, M. L. Latash and M. D. Grabiner, An apparent contradiction: Increasing variability to achieve greater precision?, *Experimental Brain Research*, vol.232, no.2, pp.403-413, 2014.
[5] J. Nishii, Y. Hashizume, S. Kaichida, H. Suenaga and Y. Tanaka, Constraint and exploitation of redundant degrees of freedom during walking, *Robotics and Autonomous Systems*, vol.60, no.5, pp.679-684, 2012.
[6] D. A. Winter, Foot trajectory in human gait: A precise and multifactorial motor control task, *Physical Therapy*, vol.72, no.1, pp.45-53, 1992.
[7] R. Begg, R. Best, L. Dell'Oro and S. Taylor, Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls, *Gait & Posture*, vol.25, no.2, pp.191-198, 2007.
[8] J. Verrel, M. Lövdén and U. Lindenberger, Older adults show preserved equilibrium but impaired step length control in motor-equivalent stabilization of gait, *PLoS ONE*, vol.7, no.12, 2012.
[9] P. M. Mills, R. S. Barrett and S. Morrison, Toe clearance variability during walking in young and elderly men, *Gait & Posture*, vol.28, no.1, pp.101-107, 2008.
[10] S. C. Carter, M. Z. Batavia, G. M. Gutierrez and E. A. Capezuti, Joint movements associated with minimum toe clearance variability in older adults during level overground walking, *Gait & Posture*, vol.75, pp.14-21, 2020.
[11] D. M. Ribeiro, G. A. S. Bueno, A. S. Guilherme, F. M. Gervásio and R. L. de Menezes, Foot-ground clearance characteristics in women: A comparison across different ages, *Gait & Posture*, vol.69, pp.121-125, 2019.
[12] S. Nakagawa and I. C. Cuthill, Effect size, confidence interval and statistical significance: A practical guide for biologists, *Biological Reviews of the Cambridge Philosophical Society*, vol.82, no.4, pp.591-605, 2007.