Age and gender differences in the control of vertical ground reaction force by the hip, knee and ankle joints

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Abstract. [Purpose] This study examined the relationships between joint moment and the control of the vertical ground reaction force during walking in the elderly and young male and female individuals. [Subjects and Methods] Forty elderly people, 65 years old or older (20 males and 20 females), and 40 young people, 20 to 29 years old (20 males and 20 females), participated in this study. Joint moment and vertical ground reaction force during walking were obtained using a 3D motion analysis system and force plates. Stepwise linear regression analysis determined the joint moments that predict the amplitude of the vertical ground reaction force. [Results] Knee extension moment was related to the vertical ground reaction force in the young males and females. On the other hand, in the elderly females, hip, ankle, and knee joint moments were related to the first peak and second peak forces, and the minimum value of vertical ground reaction force, respectively. [Conclusion] Our results suggest that the young males and females make use of the knee joint moment to control of the vertical ground reaction force. There were differences between the elderly and the young females with regard to the joints used for the control of the vertical ground reaction force.

Key words: Elderly people, Vertical ground reaction force, Lower extremity joint moment

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INTRODUCTION

In Japan, elderly individuals defined as people aged 65 years or more are known to account for more than 25% of the population. As people age, there is a concomitant decrease in muscle strength¹⁾. This age-related change affects their ability to walk²⁾. As the ability to walk of the elderly decreases, there is an associated decrease in their balance ability^{3, 4)}, and independent daily living activities⁵⁾, and they show an increased risk of fall⁶⁾. Therefore it is necessary to maintain the ability to walk of the elderly.

Ground reaction force is an external force involved in walking, which affects the acceleration of the body's center of mass⁷⁾. The vertical ground reaction force is often measured in gait analysis, and is regarded as a representative measure of walking⁸⁾. The two peaks of the vertical ground reaction force during the early stance and late stance phases reflect the support of the body's center of mass. The minimum value in the mid-stance indicates that the vertical force

applied to the ground decreases, and thus, the reaction force from the ground to the body also decreases⁹⁾.

The profile of the vertical ground reaction force correlates with many parameters of gait and functional performance, such as walking speed¹⁰⁾, the Timed Up and Go test time and the functional Reach distance¹¹⁾ in the elderly. It is also known that the vertical ground reaction force during walking is affected by aging. Elderly people exhibit lower first peak and second peak forces, and a higher minimum value at mid-stance than young people¹²⁾. The vertical ground reaction force provides correlative information about the ability to walk of elderly people. Several studies have reported that elderly individuals exhibit age-related alteration in their kinetic profiles of walking. Hip and knee joint moments of the elderly are significantly lower than those of young people¹³⁾. Moreover, DeVita and Hortobagyi¹⁴⁾ reported that elderly people showed different distributions of joint moments and powers compared to young individuals. Support during the stance phase is achieved by a net extensor pattern of moments at the ankle, knee, and hip joint¹⁵⁾. Age-related alterations in lower extremity joint moment suggest there is a difference in the support strategy between the elderly and the young.

To date, it is unclear what causes the difference in the profile of the ground reaction force between the elderly and the young. The results of our previous study¹⁶⁾ suggest that both men and women make use of different joint moments for the

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generation of antero-posterior ground reaction forces as they age, showing an age-related alteration in the motor pattern used to generate the antero-posterior ground reaction force. Moreover, if elderly people exhibit an age-related alteration in support moment of the lower extremity, changes in joint moment may affect the magnitude of the vertical ground reaction force. By analyzing the relationships between vertical ground reaction force and lower extremity joint moments, it would be possible to clarify the difference in the support strategies of elderly and young people. Therefore the purpose of this study was to examine the relationships between the vertical ground reaction force and the hip, knee, and ankle joint moments during walking by the elderly and young individuals. We hypothesized that the relation between the joint moments and vertical ground reaction force differs between the elderly and the young, similar to our previous study¹⁶⁾, and that there is an age-related change in the support strategy use for walking.

SUBJECTS AND METHODS

Forty community-dwelling elderly people, 65 years old or older (mean age, 70.1 years; age range, 65–80 years), and 40 young people, aged 20 to 29 years (mean age, 23.2 years), participated in this study. There were 20 males and 20 females in each group. The subjects were all right-handed. The exclusion criteria included neurologic disorders, osteoarthritis, rheumatic arthritis, joint pain affecting walking, and a history of surgery to the lower extremities or spine. All procedures were approved by the Hiroshima International University Human Research Ethics Committee and all participants gave their written, informed consent prior to enrollment.

In the walking trials, all the participants walked barefoot to the end of a 7 m walkway at a self-selected preferred walking speed. Data from 3 walking trials were collected. A 3D motion analysis system with 8 infrared cameras (VICON MX; Vicon Motion Systems; Oxford, UK) and 8 force plates (AMTI; Watertown, MA, USA) was used to record kinematic and kinetic data at sampling frequencies of 100 and 1,000 Hz, respectively. The force plate layout was designed to measure the ground reaction force of each limb using four force plates arranged in the longitudinal direction. Participants were instructed to walk placing their foot on the left or right force plate, avoiding stepping on two force plates simultaneously.

A total of 30 reflective markers were placed bilaterally, over the following landmarks of each participant: acromion process, olecranon, styloid process of the radius, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial and lateral femoral condyles, mid-point between the greater trochanter and the lateral femoral condyles, medial and lateral malleoli, mid-point between the lateral knee joint line and the lateral malleolus, head of the first and fifth metatarsal, and the calcaneal tuberosity. These anatomical markers were used to construct anatomical coordinate systems for the pelvis, thigh, shank, and foot segments.

The coordinates of each joint center were calculated following the description of a previous study¹⁷⁾. Kinematic and

Fig. 1. Graph representation of the vertical ground reaction forces and the joint moment of the hip, knee, and ankle during a gait cycle

kinetic calculations were performed using commercial software, “BodyBuilder” (Vicon Motion Systems). A 7-link segmental model was developed to calculate the kinematic and kinetic variables of the hip, knee, and ankle joints using the inverse dynamics technique of Davis et al.¹⁸⁾ and Vaughan et al.¹⁹⁾. Anthropometric parameters for mass, position of the center of mass, and moment of inertia for the segments were obtained from the report by Okada et al.²⁰⁾. We calculated the hip, knee, and ankle joint moments using a local coordinate system with the origin at the joint center. In this study, each joint moment was normalized to the subject’s body mass (Nm/kg).

Walking speed (m/s) was calculated using the center of gravity (COG) of the whole body, and averaged over a 3-s data collection period. Stride length (m) was measured as the antero-posterior distance between the left calcaneal tuberosity marker at one heel contact and at the next heel contact. Stride length was normalized to body height (%BH).

Initial contact was assumed to occur when the vertical reaction force exceeded 10 N, and toe off was assumed to occur in the first frame following the initial contact when the vertical reaction force fell below 10 N. To account for different builds, ground reaction force was normalized to each subject’s body mass (N/kg). First and second peaks of vertical ground reaction force, and the minimum value between the two peaks were extracted from the ground reaction force profile (Fig. 1). Peak values of each joint moment during the stance phase were extracted from the joint moment profile (Fig. 1).

Two-way analysis of variance was performed to examine the differences between the elderly and the young and the interactions between age and gender, with age, body height, body weight, body mass index (BMI), and spatio-temporal parameters. Two-way analysis of covariance was also performed to examine the difference between the elderly and the young, and the interactions between age and gender with the vertical ground reaction force, and peak values of each joint moment using walking speed as the covariate.

Step-wise linear regression was performed to determine

Table 1. Characteristics of the subject

Variable	Elderly		Young	
	Males (n = 20)	Females (n = 20)	Males (n = 20)	Females (n = 20)
Age (years)	69.45 (4.80)*	70.70 (4.62)*	22.80 (2.80)	23.50 (2.70)
Height (m)	1.64 (0.07)*	1.49 (0.04)*	1.71 (0.07)	1.57 (0.05)
Weight (kg)	62.28 (9.78)	52.09 (6.20)	64.04 (8.34)	52.91 (9.92)
BMI †(kg/m ²)	23.06 (2.96)*	23.25 (2.69)*	21.74 (2.63)	21.21 (3.30)

Value: mean (Standard deviation: SD)

*: Significant difference from the young, $p < 0.05$

†: BMI: body mass index

Table 2. Spatio-temporal parameters and peak values of joint moment

Variable	Elderly		Young	
	Males (n = 20)	Females (n = 20)	Males (n = 20)	Females (n = 20)
Walking speed (m/s)	1.20 (0.16)*	1.15 (0.12)*	1.26 (0.12)	1.29 (0.10)
Stride length (%Body Height)	73.63 (6.79)*	73.59 (5.48)*	77.47 (5.64)	81.68 (5.69)
First peak force (N/kg) §	10.57 (0.94)	10.71 (1.06)	10.96 (0.75)	10.90 (0.79)
Minimum force (N/kg) §	7.29 (0.58)	7.52 (0.58)	7.20 (0.58)	7.00 (0.60)
Second peak force (N/kg) §	10.43 (0.50)‡	9.97 (0.61)*, ‡	10.64 (0.52)	10.74 (0.51)
Hip	Extension moment (Nm/kg) †	0.76 (0.31)	0.58 (0.29)	0.72 (0.19)
	Flexion moment (Nm/kg) †	-0.67 (0.17)	-0.61 (0.17)	-0.71 (0.14)
Knee	Flexion moment during early stance (Nm/kg)†	-0.23 (0.15)	-0.21 (0.11)	-0.08 (0.17)
	Extension moment during early stance (Nm/kg)	0.58 (0.29)	0.74 (0.26)	0.71 (0.20)
	Flexion moment during terminal stance (Nm/kg)	-0.21 (0.09)‡	-0.10 (0.14)‡	-0.18 (0.12)
	Extension moment during terminal stance (Nm/kg)	0.20 (0.07)*	0.26 (0.12)*	0.17 (0.08)
Ankle	Dorsiflexion moment (Nm/kg)	-0.21 (0.10)	-0.24 (0.11)	-0.25 (0.08)
	Plantarflexion moment (Nm/kg)†	1.16 (0.22)*	1.02 (0.16)*	1.30 (0.11)

Value: mean (Standard deviation: SD)

*: Significant difference between age groups, $p < 0.05$ †: Significant difference between gender groups, $p < 0.05$ ‡: Age $\times$ gender interaction, $p < 0.05$

§: Vertical ground reaction force

the joint moments that predicted the amplitude of vertical ground reaction force in the elderly men, elderly women, young men, and young women. Relationships among the peak values of the hip, knee, and ankle joint moments during the early stance phase and the first peak force, and the minimum value of the vertical ground reaction force, were investigated. Relationships among the peak values of the hip, knee, and ankle joint moments during the late stance phase and the second peak force of the vertical ground reaction force were also investigated. The stepping-method criteria were: an F -value of ≥ 0.05 for inclusion in the segmental model, and ≤ 0.10 for removal from the model.

Statistical significance was accepted for values of $p < 0.05$. All data were analyzed using SPSS 17.0 statistical software (SPSS Japan Inc., Tokyo, Japan).

RESULTS

The baseline demographic characteristics of the study subjects are presented in Table 1. The elderly participants had significantly shorter body height and higher BMI than the younger study participants, but there was no significant

difference in their body masses.

The spatio-temporal parameters and peak values of joint moment are presented in Table 2. The elderly males and females had significantly slower walking speeds, with shorter stride lengths than the young participants, but there was no significant difference in cadence between the two age groups. The second peak of the vertical ground reaction force exhibited a significant interaction between age and gender, and the elderly females had a significantly lower second peak of vertical ground reaction force than the younger females. There was an approximately 7.5 percent difference between the elderly females and the young females groups. The plantar flexion moment of the ankle was lower in the elderly participants. On the other hand, the extension moment during the terminal stance phase of the knee was higher in the elderly participants. There were approximately 14.5 and 30.0 percent differences between the elderly and the young groups of both males and females, respectively. Although the flexion moment during the terminal stance phase of the knee exhibited a significant interaction between age and gender, there was no significant difference between the age groups, neither in males nor in females.

Table 3. Models of the vertical ground reaction force by forward step-wise regression analysis.

Subject	Independent variable	Unstandardized coefficient	Standardized coefficient	Adjusted R ²
First peak force [†]				
Elderly female	Hip extension moment	2.14*	0.61	0.34*
Young female	Knee extension moment during early stance	1.35*	0.47	0.22*
Minimum value at mid-stance [†]				
Young male	Knee extension moment during early stance	-1.95*	-0.69	0.48*
Elderly female	Knee extension moment during early stance	-1.31*	-0.51	0.26*
Young female	Knee extension moment during early stance	-1.04*	-0.54	0.29*
Second peak force [†]				
Young male	Knee extension moment during late stance	2.67*	0.45	0.21*
Elderly female	Ankle plantarflexion moment	2.22*	0.57	0.33*

*: $p < 0.05$

†: Vertical ground reaction force

The results of step-wise linear regression analyses of vertical ground reaction force are presented in Table 3, and the joint moments related to the vertical ground reaction force are shown in Fig. 2. Elderly males exhibited no statistically significant factors related to the vertical ground reaction force.

For the young males and females, and elderly women groups, the knee extension moment during the early stance phase was related to the minimum value of the vertical ground reaction force at mid-stance.

For young males, the knee extension moment during the late stance phase was related to the second peak of the vertical ground reaction force. On the other hand, for young females, the knee extension moment during the early stance phase was related to the first peak of the vertical ground reaction force. In contrast, for the group of elderly females, the hip extension moment was related to the first peak of the vertical ground reaction force, and the ankle plantarflexor moment was related to the second peak of vertical ground reaction force.

DISCUSSION

This study examined the relationships between the vertical ground reaction force and hip, knee, and ankle joint moments during walking in young and elderly individuals. The analyses of this study were performed in consideration of gender as well as age. This was done because a previous report²¹⁾ indicated that there are significant gender differences in walking speed, stride length, kinematics and kinetics. In this study, some parameters exhibited a significant gender difference and interaction between age and gender. Thus, in order to maximize the ability to determine the effects of age on walking, the study subjects were divided by gender.

The first peak and the minimum value at mid-stance of the vertical ground reaction force were not significantly different between the elderly and the young. On the other hand, the second peak of the vertical ground reaction force of the elderly women was significantly lower than that of the young women. Yamada and Maie¹¹⁾ reported that elderly people have lower first peak and second peak forces, and a

Fig. 2. The joint moments that can predict the amplitude of the vertical ground reaction force in each group

higher minimum value at mid-stance than younger people. On the other hand, Larish et al.²²⁾ reported that there was no significant difference in the first peak force, but a significant difference in the second peak of the vertical ground reaction force. Because the amplitude of the peak vertical ground reaction force is affected by cadence rather than stride length²³⁾, there may be no difference between the elderly and young people in the first peak of the vertical ground reaction force. Both the first and second peaks of the vertical ground reaction force correspond to the upward acceleration of the body center of mass⁸⁾. The elderly females in this study had low upward acceleration of body center of mass at push-off. This may increase the load on the front limb when producing upward acceleration during the double support phase of elderly females.

The plantar flexion moment of the ankle of the elderly was smaller by approximately 14.5 percent than that of the

young people. Therefore, the plantarflexor muscles of the elderly exhibited an age-related functional decline. Young people used 40% of their maximum plantar flexor moment during walking²⁴). The plantarflexor during walking exerts the largest force. Therefore, it is important for the elderly to strengthen the ankle plantarflexor.

Knee extension moment during early stance had a negative relationship with the minimum value at mid-stance, and the knee extension moment during late stance had a positive relation with the second peak of the vertical ground reaction force of the young males. The knee extension moment during early stance had a positive relation with the first peak force, and a negative relation with the minimum value at mid-stance of the ground reaction force of the young females. These results suggest that the vertical ground reaction force may be controlled by knee extension in young people. In our previous study¹⁶), the knee extension moment during late stance was associated with the anterior component of the ground reaction force of young males, and the knee joint moment was associated with the antero-posterior component of the ground reaction force of young females. The knee extension moment of young people is important for decreasing the reaction force from the ground to the body at mid-stance, and increasing the ground reaction force during weight acceptance and the push off phase. It is necessary to have muscle strength in order to increase the joint moment during walking. Brown et al.²⁵) reported that there was a relationship between quadriceps strength and walking ability, especially in young people rather than in the elderly. Therefore knee joint function is important for support during walking by young people.

In the elderly females of this study, the extension moment of the hip had a positive relationship with the first peak of the ground reaction force. In our previous study¹⁶), the extension moment of the hip was associated with the posterior component of ground reaction force in elderly females, and the present result is consistent with the result of that previous study. The elderly females had a large hip extension moment, and their ground reaction force during the early stance phase was relatively high. Although the knee joint moment was associated with the first peak of the vertical ground reaction force in the young females, the hip joint moment was associated with the first peak of the vertical ground reaction force in the elderly females. The elderly and young females in this study made use of different joints to control of the vertical ground reaction force. These results are mostly consistent with our hypothesis that there is an age-related change in the support strategy of walking. Support for the body is provided by a combination of knee extensors and hip extensors during the early stance phase²⁶). Elderly people have significantly weaker quadriceps and hamstrings muscle strength than young people²⁷). While walking, moreover, elderly people had more forward trunk lean, and a large hip flexion angle during early stance¹⁴). Because the function of the muscles surrounding the knee joint reduces with aging in addition to age-related alteration in the attitude of walking, weight acceptance during the early stance phase of the elderly is accomplished by the hip joint. For weight acceptance in the initial stance, therefore, it is necessary for elderly females to develop a hip extensor.

The extension moment during the early stance phase of the knee had a negative relationship with the minimum value of the ground reaction force at mid-stance in the elderly females. This result was similar to the one found for the young females in this study. In order to reduce the mechanical load exerted on the body at mid-stance, it may be important for elderly females to strengthen the quadriceps muscles, and generate a knee extension moment during early stance. Moreover the plantarflexion moment of the ankle had a positive relationship with the second peak of the ground reaction force of the elderly females. Winter¹⁵) reported that the ankle plantarflexion moment was the major contributor to support during push-off. The rate of decline in maximal voluntary isometric force with aging is greatest in the plantar flexors²⁸). It is probable that because the elderly females had a lower plantarflexion moment of the ankle than that of young females, the second peak of the vertical ground reaction force was smaller in the elderly females in this study. A previous study reported the importance of plantarflexor muscles of the ankle during walking by the elderly²⁹). Therefore it is important to strengthen the plantarflexor muscles of the ankle of elderly females in order to enhance support during late stance.

In contrast, no factors related to the first peak and second peak forces and the minimum value of the vertical ground reaction force of the elderly males were found. It has been reported that the contribution of joint moment to the antero-posterior ground reaction force is small in elderly males¹⁶). Because individual variation was greater among the elderly males, factors related to the vertical ground reaction force were found not to be significant, similar to the antero-posterior ground reaction force. The changes in physical function with aging are not equal in males and females³⁰), and physical characteristics, lifestyle, and social background are different between males and females. Therefore there are gender differences in the age-related changes of walking characteristics, and elderly males make use of various joint moment patterns to the control of the vertical ground reaction force.

The present study had several limitations. The relationship between the vertical ground reaction force and lower extremity joint moments during walking in both elderly and young subjects were investigated. However, step-wise linear regression analysis did not find a factor related to the vertical ground reaction force in several models, because we analyzed the data divided by age and gender. Using mechanical analysis using equations of motion, Kepple et al.²⁶) showed that support of the body was provided by the ankle plantarflexor moment during single limb support, and by a combination of ankle plantarflexors, knee extensors, and hip extensors during double-limb support in younger people. Therefore in order to clarify the age-related changes in walking mechanism of elderly people, it will be necessary to perform detailed analyses of dynamic equations of motion. Furthermore, we were unable to identify the causative factor of age-related changes in the support strategy of walking. Further studies are required to determine the causes of changes in strategy with aging.

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