Age-specific and sex-related changes of gait in the Japanese elderly

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Age-specific and sex-related changes of gait in the Japanese elderly

日本人高齢者における歩行動作の加齢変化および性差

Irma Nur Afiah

November, 2016

Abstract

The objectives of this dissertation were to investigate the effect of aging on gait parameters in Japanese elderly, to clarify whether age-related changes in gait characteristics are consistent and continue with advanced age when subcategorizing according to early and late elderly, and to investigate the differences according to sex in gait characteristics between elderly Japanese men and women. Three studies were conducted in order to investigate: 1) age-related changes in the walking motion of elderly Japanese women; 2) age-related changes in the walking motion of elderly Japanese men; and 3) sex-specific differences in the walking motion of Japanese elderly. The first study indicated that the timing of peak joint angle and angular velocity parameters are the main characteristics that define gait changes in the elderly. Very elderly women showed a cadence-dependent walking pattern, and delayed peak timing of joint angle and angular velocity during the critical phases throughout the gait cycle (pre-swing, initial swing, and terminal swing phases). These delays in peak timing primarily reflect the unique joint behavior in very elderly women. The second study extended the same investigation for elderly Japanese men. The specific gait characteristics of very elderly men were slower walking speed, smaller cadence, delayed peak timing at the hip and knee joint, smaller first peak plantar flexion angular velocity, and greater second peak plantar flexion angular velocity at the ankle joint. The third study investigated sex differences between elderly Japanese men and women. Sex-specific differences in walk ratio, the hip maximal angle range, peak extension timing at the hip joint, and second peak flexion timing at the knee joint are peculiar in elderly individuals. In conclusion, the results of this dissertation would be useful for identifying and monitoring parameters that reflect the gait characteristics in the elderly population. In addition, the findings of this dissertation could be used to improve the health care system and would be necessary to assist well-being, nursing, rehabilitation of motor disorders, and to prevent walking ability deterioration in this population.

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Chapter 1

General Introduction

1.1 Aging as a global issue

It is widely agreed that the population of older individuals is increasing dramatically in the majority of countries, both developed and developing countries. According to a report released by United Nations Department of Economic and Social Affairs in 2015, 12% of world's population were older individuals aged 60 years or over. According to East-West Center (2010), the number of people aged 65 and over is expected to grow dramatically in the next 60 years in Asia, whereby older women will outnumber older men. Furthermore, aging is not only an immediate personal issue, but also a significant factor in crucial public policies, such as pensions, health care, and long-term care (Muramatsu and Akiyama 2011). Generally, the furthest along countries in the population-aging process are in East Asia and are followed by countries of Southeast Asia, and of South Asia (East-West Center 2010).

Elderly population growth in Japan is evident. The number of Japanese elderly is increasing and life expectancy also continues to increase (Cortazzi 2015). Japan's socio-economic system has already been substantially affected by rapid population aging and the welfare of older persons is likely to be affected in the future (Ogawa and Matsukura 2007). Approximately, two-thirds of older Japanese adults currently engage in no regular leisure-time physical activity (Yasunaga et al. 2008).

Increasing elderly population and life expectancy are related to the quality of life of this population (Demura et al. 2012; Roppolo et al. 2012). Generally, the quality of life is considered a critical component of public health, as it is decisive for the physical activities recommended for elderly individuals (Guallar-Castillon et al. 2004). Particularly, the adequate habitual physical activity is necessary for health promotion, disease prevention, and delaying the functional loss in elderly individuals (Yasunaga et al. 2008). Loss of physical function due to aging affects the ability to perform the essential activities of daily living (ADLs) (Penninx et al. 2001; Covinsky et al. 2003). ADLs are fundamental to maintaining independence and the quality of life of older individuals (Covinsky et al. 2003). Therefore, maintaining functional independence in ADLs (included walking, bathing, grooming, etc.) and improving the quality of life are mandatory (Hachisuka et al. 1998; Wada et al. 2005).

1.2 Walking ability decline with age

Loss of independence is one of main issues of the aging process (Kirkwood et al. 2007; Callisaya et al. 2010; Kimura et al. 2012; Demura et al. 2013). Advanced age causes some difficulties in locomotive activities, including walking. The ability to walk efficiently and safely is important for elderly individuals to maintain their independence (Callisaya et al. 2010). Several studies reported how aging affects the independence of walking in older adults (Alexander 1996; Bohannon and Eriksrud 2001; Menz et al. 2003; Frank and Patla 2003; Toebes et al. 2012; Demura et al. 2013; Verlinden et al. 2013; Hillcoat-Nalletamby 2014). For instance, Menz et al. (2003) reported that older individuals showed reduced vision, peripheral sensation, and limb strength, that affected their walking ability. Additionally, the decline in walking ability is associated with increased risk of falls, hospitalization, and subsequent physical and cognitive decline (Jerome et al. 2015).

The deterioration of walking ability in older individuals can be distinguished by several changes in some biomechanical characteristics of habitual gait. Generally, older individuals exhibit a modified gait pattern compared to the young individuals by adopting specific movement strategies as a response to the alterations in musculoskeletal function (Alcock et al. 2013). Furthermore, older individuals would select a slower walking speed with a shorter step/stride length and shorter duration of swing phase (DeVita and Hortobagyi 2000) The changes in cadence and step length would affect walking speed and duration of gait cycle in elderly; shorter duration of gait cycle and smaller cadence showed that older individuals required more time to cover the same distance than younger counterparts (Afiah et al. 2014a). Additionally, age-related decline in walking ability could be determined from changes in specific joint angle movements. For instance, older individuals walked with smaller hip range of motion and plantar flexor strength than young adults, and this was a major characteristic of gait in elderly (Anderson and Madigan 2014). In addition, the decrease of the lower-limb muscle strength and leg strength affects mobility in older individuals, contributing primarily to the deterioration in walking stability (Savelberg and Meijer 2004; Shin et al. 2012).

The contribution of lower extremities (including the hip, knee, and ankle joint) to gait mechanism has been recognized in several previous studies (Winter 1984; Crosbie et al. 1997a; DeVita and Hortobagyi 2000; Terrier and Reynard 2015).

Terrier and Reynard (2015) stated that significant strength loss in the lower extremities begins around the age of 40 to 50 years. Moreover, DeVita and Hortobagyi (2000) also reported that elderly individuals generate decreased joint torques and powers in the lower extremities. Throughout one gait cycle, older adults generated less positive work at the ankle and more positive work at the hip compared to the younger adults, and this phenomenon occurs with normal aging (DeVita and Hortobagyi 2000; Silder et al. 2008). Additionally, the reduction in knee flexion, the increment in ankle plantar flexion, and the alteration of swing phase were general gait characteristics often reported with advanced age (Alcock et al. 2013).

Currently, the majority of geriatric rehabilitation centers focus on restoring the walking ability in a wide range of medical diagnoses (Chui and Lusardi 2010). Several differences in gait performance of individuals at early and late old ages have been reported (Alexander 1996; Chui and Lusardi 2010; Salzman 2010; Thaler-Kall et al. 2015). For instance, difficulty in walking and decrease comfortable gait speed occur after the age of 63 years (Alexander 1996). Furthermore, people aged 70 years and greater must pay more attention to the complex tasks of walking in order to reduce the risk of falls (Thaler-Kall et al.

2015). Falls during walking are a major health issue in older individuals, as they are detected in approximately 60% of those 80 to 84 years of age (Salzman 2010) and are primarily caused by gait and balance disorders (Terrier and Reynard 2015). Consequently, a better understanding of the age-related decline in walking ability and the assessment of specific gait characteristics of persons at early and late old age might be useful for well-being, nursing, and the rehabilitation of motor disorders. In addition, understanding gait characteristics of the elderly and how gait is affected by aging can prevent dysfunction and loss of independent ambulation (Kirkwood et al. 2007; Callisaya et al. 2009; Salzman 2010).

1.3 Sex-specific differences in gait characteristics

In addition to age, sex-specific differences play an important role for gait characteristics (Cho et al. 2004; Demura et al. 2008; Bruening et al. 2015). Sex-specific differences in skeletal dimension affect the gait patterns (Cho et al. 2004). For instance, younger women walked with higher cadence and shorter stride length than men due to their short height (Cho et al. 2004) and younger women also demonstrated greater peak foot pronation angles compared to men as a strategy of absorbing energy (Kernozek et al. 2007). In addition, adult women increase their knee range of motion throughout the gait cycle in order to provide an anterior cruciate ligament loading environment compared to their counterparts (Decker et al. 2003).

The gait parameters often used to compare gait characteristics between women and men are walking speed, cadence, stride length, and changes in the range of motion at the hip, knee, and ankle joints (Decker et al. 2003; Ko et al. 2011; Bruening et al. 2015). Furthermore, the majority of previous studies investigated sex differences in gait between young or adult men and women (Decker et al. 2003; Ferber et al. 2003; Cho et al. 2004; Kernozek et al. 2007). Other studies included middle-aged and older individuals and therefore the age range in these studies was wide (Crosbie et al. 1997a; Hachisuka et al. 1998; Callisaya et al. 2008; Ko et al. 2011). Therefore, this dissertation focused on the investigation regarding sex differences on gait characteristics among elderly Japanese men and women aged over 65 years.

1.4 Gait motion throughout the gait cycle

Generally, gait motion is described and characterized in the context of the gait cycle (Umberger 2010). The gait cycle is divided into 2 phases: stance and swing (Ayyappa 1997). The stance phase begins with the initial contact of the foot to the ground and continues till the foot is on the ground, while the swing phase begins as the foot is lifted from the floor (also known as toe-off) (Perry and Burnfield 2010). In a complete gait cycle, two components are related to the limb-support, namely single support and double support phases. Double support phase indicates that both feet are on the floor simultaneously (Vieira et al. 2015), while the single support phase is the period when only one foot is in contact with the ground (Ayyappa 1997). Specifically, the stance phase is subdivided into 5 phases, namely initial contact, loading response, mid-stance, terminal stance, and pre-swing phases (Figure 1.1). Meanwhile, 3 phases are involved in the swing phase, namely initial swing, mid swing, and terminal swing phases (Rancho Los Amigos National Rehabilitation Center 1989; Perry and Burnfield 2010). Each of 8 specific gait phases has a functional objective and a critical pattern in order to complete one gait cycle. Additionally, the combination of these phases enables the limb to accomplish 3 basic tasks: weight acceptance, single limb support, and swing limb advancement (Perry and Burnfield 2010),

During walking, when the foot first contacts the floor, all leg joints play important roles. At the beginning of the stance phase, using the heel as a rocker, the knee is flexed for shock absorption and weight-bearing stability until the end of the loading response phase (Perry and Burnfield 2010). Furthermore, the single limb support continues the stance phase with mid stance and terminal stance (Liu et al. 2009). At these phases, the hip and knee are extended while the limb advances over the stationary foot by the ankle dorsiflexion (Perry and Burnfield 2010).

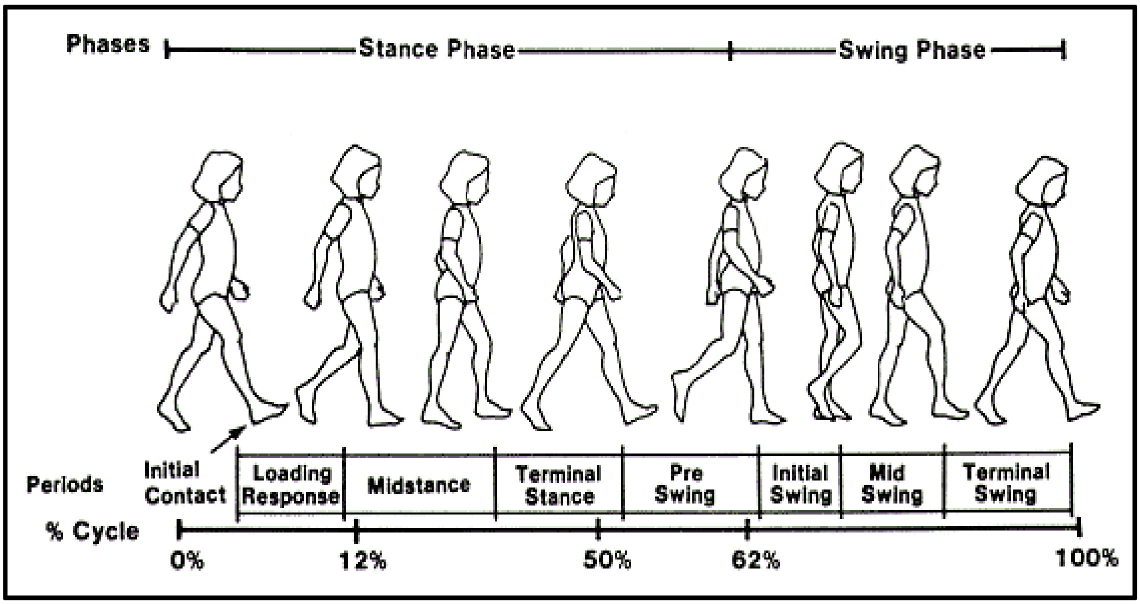

Figure 1.1 Division of the gait cycle

(Kirtley 2006)

At the end of the stance phase, also known as the pre-swing phase, the reference limb responds with increased ankle plantar flexion, greater knee flexion, and hip extension in order to initiate the forward motion that is used in the swing phase (Perry and Burnfield 2010; Kharb et al. 2011). Moreover, all leg joints contribute to optimize the swing limb advancement by moving the limb forward from its trailing position during the initial and mid swing phases. During the initial swing phase, knee flexion is performed to facilitate toe clearance, while hip flexion advances the limb, and ankle dorsiflexion is complete (Nene et al. 1999; Perry and Burnfield 2010). Subsequently, the knee extends and the ankle continues dorsiflexion to neutral until the end of mid swing phase (Kharb et al. 2011).

Finally, in the terminal swing phase, the limb is decelerated in order to prepare for the heel strike, which will terminate the swing phase and also will indicate the end of one complete gait cycle (Rueterbories et al. 2010). During this phase, the limb advancement is completed by knee extension and the ankle remains in dorsiflexion to neutral (Perry and Burnfield 2010; Kharb et al. 2011). All leg joints contribute to prepare the limb for the next initial contact.

1.5 Gait parameters and its measurement

The most commonly reported gait parameters are the spatial and temporal parameters. Walking speed and step/stride length are defined as spatial parameters, while time of swing phase, time of stance phase, time of one gait cycle, and double/single support durations are temporal parameters. Most previous studies focused on spatial-temporal parameters (Kimura et al. 2007; Callisaya et al. 2008; Callisaya et al. 2010; Schulz 2012; Afiah et al. 2014a; Afiah et al. 2014b; Vieira et al. 2015) and several of studies combined them with other general gait parameters, including kinematic and/or kinetic parameters (Moyer et al. 2006; Kirkwood et al. 2007; Lee et al. 2013). Recently, the gait parameters often used in order to identify gait characteristics among elderly, with respect to sex differences, are joint angle movements, including flexion/extension and plantar flexion/dorsiflexion of the hip, knee, and ankle joints (Cho et al. 2004; Savelberg and Meijer 2004; Kernozek et al. 2007; Doyo et al. 2011; Ko et al. 2011; Demura et al. 2013; Alcock et al. 2013; Bruening et al. 2015). For example, Alcock et al. (2013) identified the alteration in gait mechanics by analyzing hip flexion/extension, knee flexion/extension, and ankle plantar flexion/dorsiflexion. This study found age-related changes only at the hip and ankle, while the knee joint was not affected by aging. Furthermore, Demura et al. (2013) analyzed only hip flexion and knee extension to examine the relationship between the walking ability and the fall risk of elderly. With respect to sex-specific differences, primary used gait parameters were maximal angle range, cadence, and joint angle movements at hip, knee, and ankle joints (Cho et al. 2004; Ko et al. 2010).

Since the majority of previous studies extensively focused only on differences between younger and older individuals, this dissertation would investigate how aging and sex differences affect gait characteristics among elderly. Several gait parameters might be peculiar among elderly individuals, namely the peak value and peak timing throughout gait cycle. The peak timing parameters in this dissertation are introduced as the reliable gait parameters, because these parameters could represent the timing of joint angle displacement and the timing when the angular velocity of joint instantaneous change in flexion/extension or plantar flexion/dorsiflexion throughout one gait cycle. Particularly rigorous measurement is necessary for the walking speed condition to enhance the representative of natural walking speed in elderly individuals. To achieve this objective, participants should be instructed to walk as naturally as possible, at a self-selected comfortable pace similar to that performed in their daily life.

1.6 General objectives and research plan

The main goal of this dissertation is to provide a new insight into age-related changes of walking motion among the elderly Japanese. Three specific objectives of this dissertation were to investigate the effect of aging on gait parameters in Japanese elderly, to clarify whether age-related changes in gait characteristics are consistent and continue with advanced age when subcategorizing according to early and late elderly, and to investigate the differences according to sex in gait characteristics between elderly Japanese men and women. The investigation included 3 necessary studies. The first study focused on the investigation of age-related changes in elderly Japanese women. The second extended the same investigation for elderly Japanese men. These main studies proposed new gait parameters that strongly reflect the walking motion related to the aging process. The third study was conducted to investigate sex differences in gait parameters of Japanese elderly.

1.7 Structure of the dissertation

This dissertation is divided into five chapters:

Chapter 1: General introduction

This chapter describes the aging issues and its relationship with the quality of life. This chapter also describes how aging affects walking ability in elderly individuals, a brief introduction regarding sex differences of gait characteristics, and the importance of gait assessment to prevent deterioration of walking ability. A brief introduction with respect to gait motion throughout the gait cycle, general gait parameters, and their measurement is also provided. This chapter explains the general objective of the study and summarizes the research plan.

Chapter 2: Aging-related changes in the walking motion of elderly Japanese women

In this chapter, we report a study published in SpringerPlus (DOI: 10.1186/s40064-016-2739-7; Irma Nur Afiah, Hiroki Nakashima, Ping Yeap Loh, Satoshi Muraki) on July 13, 2016. The purposes of this study were to investigate the effect of aging on gait parameters in elderly Japanese women and to identify parameters that are reflective of gait characteristics in the elderly population.

Chapter 3: Aging-related changes in the walking motion of elderly Japanese men

The objectives of this chapter were to investigate the effect of aging on gait parameters in elderly Japanese men and to detect parameters that reflect the walking motion upon aging in the Japanese population.

Chapter 4: Sex-specific differences in walking motion for healthy, elderly Japanese individuals

The objectives of this study were to investigate differences in gait parameters according to sex in healthy, elderly Japanese individuals and to identify specific gait characteristics of elderly men and women

Chapter 5: General discussion

This chapter summarizes the results described in Chapters 2, 3, and 4, including the general discussions, the implications, the limitations, future research priorities, and general conclusion of this dissertation.

Chapter 2

Age-related changes in the walking motion of elderly Japanese women

2.1 Introduction

Japan has one of the highest life expectancies, with Japanese women living to an average of 87 years old (World Health Organization 2016). Increases in the elderly population and life expectancy are related to quality of life (Demura et al. 2012; Roppolo et al. 2012), which is influenced by many factors, such as physical activity, environmental factors, social interaction, and demographics (Drewnoski and Evans 2001; Pernambuco et al. 2012; Sun et al. 2015; Heesch et al. 2015; Gao and Li 2016).

Gait, the act of walking or running in humans, is a fundamental daily physical activity (Kerrigan et al. 1998; Perry and Burnfield 2010; Baker 2013). However, advanced age can result in locomotive difficulty; specifically, with respect to walking, which is the most common of all human movements and is greatly affected by age (Winter 1991; Whittle 2007; Callisaya et al. 2008; Callisaya et al. 2010). Furthermore, walking is influenced by sex and physical condition (Whittle 2007). Accordingly, assessment of gait characteristics is essential to prevent deterioration of walking ability with advanced age. Numerous studies have addressed the changes in gait characteristics of the elderly (Watelain et al. 2000;

Arif et al. 2002; Callisaya et al. 2008; Lord et al. 2013). For example, Winter et al. (1990) reported that gait characteristics are involved in a reduction in walking speed, due to a shorter stride length. Similarly, shorter step lengths and a progressive limiting of the range of motion at the ankle have been observed in the elderly (Hageman and Blanke 1986). Changes in gait characteristics of the elderly can also be identified in joint movement angles (Savelberg and Meijer 2004; Kimura et al. 2007; Kirkwood et al. 2007).

In general, a reduction in muscle strength and lower extremity function, impaired mobility, and lower activity levels by age 70 have been well documented (Guralnik et al. 1995; Winegard et al. 1996; Drewnoski and Evans 2001; Silder et al. 2008). Many previous studies have investigated age-related changes in gait variability. The majority of these studies have noted comparable gait characteristics between younger and older study groups (Mills and Barrett 2001; Grabiner et al. 2001; Moyer et al. 2006; Kang and Dingwell 2008; Schulz 2012; Vieira et al. 2015). A number of studies have previously investigated age-related changes in very elderly individuals; however, analysis of gait parameters has been limited (Kirkwood et al. 2007; Callisaya et al. 2010). In the present study, elderly Japanese women were classified into 2 subcategories, elderly and very elderly, to provide insight into whether age-related changes in gait characteristics are consistent and continued with advanced age. Moreover, it is necessary to identify gait parameters that are more reliable indicators of change in walking motions with advanced age. Spatial and temporal parameters are insufficient for a rigorous understanding of gait characteristics in elderly individuals. Despite growing agreement regarding the existence of age-related changes in gait characteristics, there is a lack of understanding regarding the changes themselves and appropriate parameters for evaluating these changes. When walking is observed using 3D motion analysis, many different parameters can be assessed. In the present study, timing-related parameters for evaluating age-related changes in gait are proposed; namely, the timing of joint angle and angular velocity peak values throughout the gait cycle. To improve the assessment of walking, it is necessary to identify parameters strongly associated with the walking motion in elderly.

In this study, basic gait parameters, gait cycle parameters, joint angle parameters, and angular velocity parameters were evaluated. Basic gait parameters included walking speed, step/stride length, and cadence, which are regarded as the most frequently used time-distance parameters for evaluating gait and walking patterns (Oberg et al. 1993; Whittle 2007; Thakurta et al. 2016). To obtain a better understanding of gait motion in elderly Japanese women, with respect to joint angle and angular velocity parameters, the peak joint angle and timing thereof were also obtained. The primary purpose of this study was to investigate the effect of aging on gait parameters in elderly Japanese women. The second purpose was to identify parameters that are reflective of gait characteristics in the elderly population. We hypothesized that differences in gait would exist among elderly and very elderly women.

2.2 Material and methods

2.2.1 Participants

Data were collected from 49 healthy elderly Japanese women, who were divided into 2 groups: (1) 30 elderly women (65 to 74.9 years old) with a mean age of 70.4 ± 2.4 years, and (2) 19 very elderly women (≥ 75 years old) with a mean age of 78.4 ± 2.7 years. In this study, all participants were right-leg dominant. General study group characteristics are shown in Table 2.1.

All participants were screened prior to the start of the study using a medical questionnaire. The purpose of screening evaluation was to ensure that participants did not have any serious orthopaedic symptoms in the lower-limb, and were capable of independent walking. This study was approved by the Ethics Committee, Faculty of Design, Kyushu University, and written consent was obtained prior to study procedures.

Table 2.1 Participant characteristics

	Group 1 (Elderly women)	Group 2 (Very elderly women)	*p* value
Age *(years)*	70.4 ± 2.4	78.4 ± 2.7	< 0.01
Height *(cm)*	152.7 ± 5.6	148.4 ± 4.8	< 0.01
Weight *(kg)*	50.8 ± 8.5	47.9 ± 7.4	NS
Lower-limb length *(cm)*	69.5 ± 3.6	66.9 ± 2.8	< 0.05

NS: Not significant. All values are presented as mean +/- standard deviation.

2.2.2 Procedures

A 3D motion analysis system, consisting of 9 infrared cameras and Cortex software (Motion Analysis Corporation, Santa Rosa, CA, USA), was used to collect kinematic data. Participants were required to wear clothes in firm contact with the skin. Thirty-one trajectory markers were attached for each participant to the main bodily segments; head, upper limb (shoulder, elbow, wrist, spinal column, and sacrum), leg along the superior iliac spine, greater trochanter, lateral joint line of the knee, lateral malleolus, and toe.

2.2.3 Measurements

Participants were asked to walk barefoot on a flat surface for 10 metres at a self-selected speed. Prior to any measurements, participants were also instructed to practice walking barefoot. A self-selected speed measurement was recorded for each participant with the aim of defining a representative gait pattern, as performed in daily life. In this study, 3 measurements were recorded to eliminate variation in walking speed and to enhance the reliability and accuracy of the average taken from these values. Additionally, as reported by Sadeghi et al. (2002), Ko et al. (2010), and Singer et al. (2013), 3 trials are recommended for gait measurement, as a means of obtaining the most natural stride and gait patterns for each individual.

2.2.4 Gait parameters

All gait parameters were analysed using KineAnalyzer software (Kissei Comtec, Nagano, Japan). In total, 57 gait parameters were measured in this study: 7 basic gait parameters (walking speed, stride length, step length, ratio of step length to height, ratio of step length to lower-limb length, cadence, and walk ratio), 7 gait cycle parameters (duration of swing phase, duration of stance phase, duration of one gait cycle, swing phase percentage, stance phase percentage, single support percentage, and double support percentage), joint angle parameters, and angular velocity parameters.

Furthermore, 21 joint angle parameters at the hip, knee, and ankle joints were analysed. At the hip and knee joints, the peak extension and flexion angles, in combination with timing of peak values and the maximal angle range, were identified. At the ankle joint, the peak plantarflexion and dorsiflexion angles, in combination with timing of peak values and the maximal angle range, were identified. Additionally, 22 angular velocity parameters were analysed. The peak extension and flexion angular velocities and timing of peak values were identified at the hip joint and knee joint, whilst the same parameters were identified for peak plantarflexion and dorsiflexion at the ankle joint.

Walking speed was calculated using step length multiplied by cadence. Stride length was measured between consecutive heel strikes of the same foot. Right step length and left step length were measured as the distance between the point of initial contact of one foot and the point of initial contact of the opposite foot. Step length was calculated as the average of right and left step lengths. Subsequently, the ratios of step length to height and step length to lower-limb length were derived. Cadence was defined as the number of steps taken in a given time, and walk ratio was calculated as the ratio of step length to cadence.

Phases in the gait cycle were evaluated according to duration. The duration of the right swing phase was defined as the time when the right foot was off the ground, while the right stance phase was defined as the time when the right foot was on the ground. Similarly, the duration of the left swing phase was defined as the time when the left foot was off the ground, while the left stance phase was the time when the left foot was on the ground. The single support phase was defined as the period of time during which the opposite foot was lifted for swing phase, whilst the double support phase was defined as the period when both feet were in contact with the floor. The gait cycle was defined as the time interval between two successive occurrences of one repetitive event of walking.

The percentage of total duration attributable to the swing phase was calculated using the duration of the swing phase and gait cycle. The same calculation was performed to determine the percentage of total duration attributable to the stance, single support, and double support phases, using the corresponding phase durations.

Joint angle parameters were also obtained. The angle at the hip joint was measured from 2 points on the body segment (greater trochanter and knee) with reference to the horizontal plane. Similarly, the knee joint was measured from 3 points on the body segment; specifically, the greater trochanter, knee, and lateral malleolus. Finally, the ankle joint was measured from 3 points on the body segment, including the knee, lateral malleolus, and toe. With respect to the hip joint angle, a positive value was taken to indicate hip extension, while a negative value indicated flexion. The peak extension angle was detected during the pre-swing phase, and the peak flexion angle was detected during the mid-swing phase; the maximal angle range was calculated between these maximal values (Figure 2.1).

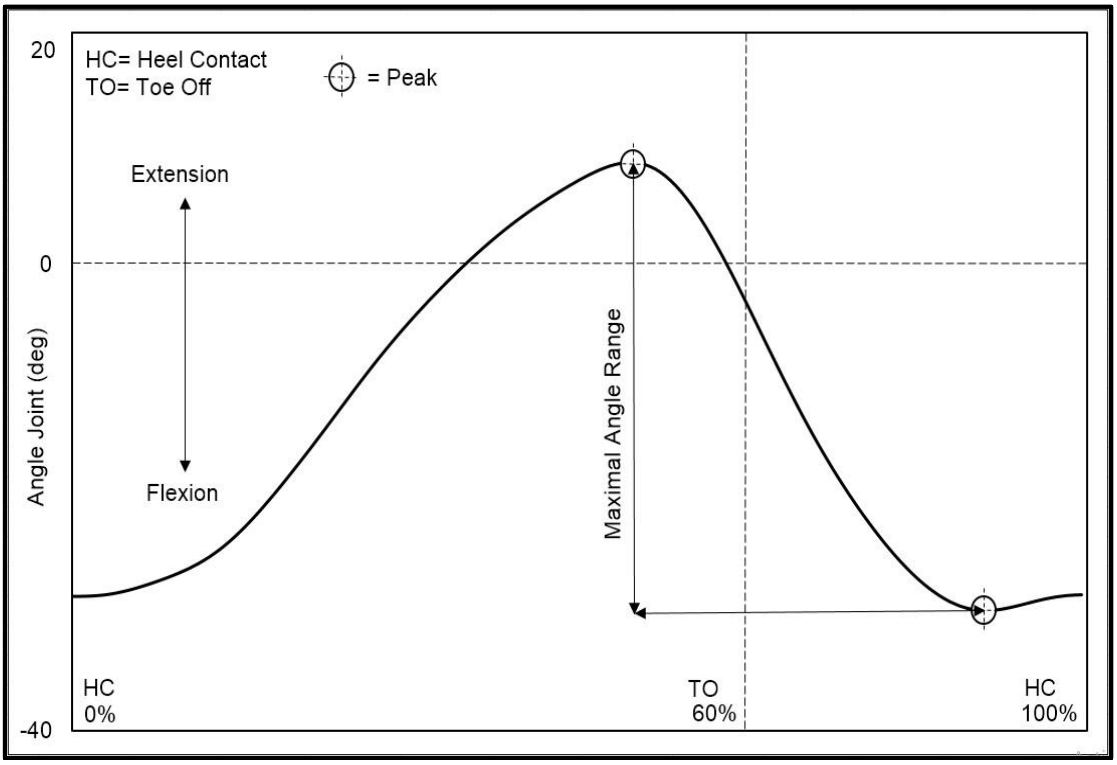

Figure 2.1 Hip joint angle

At the knee joint, an increase in angle indicated extension of the knee, while a decrease was taken to indicate knee flexion. The peak extension angle was detected during the terminal stance phase, the first peak flexion angle during the mid-stance phase, and the second peak flexion angle during initial swing phase; the maximal angle range was calculated from the peak extension angle to the second peak flexion angle (Fig. 2.2).

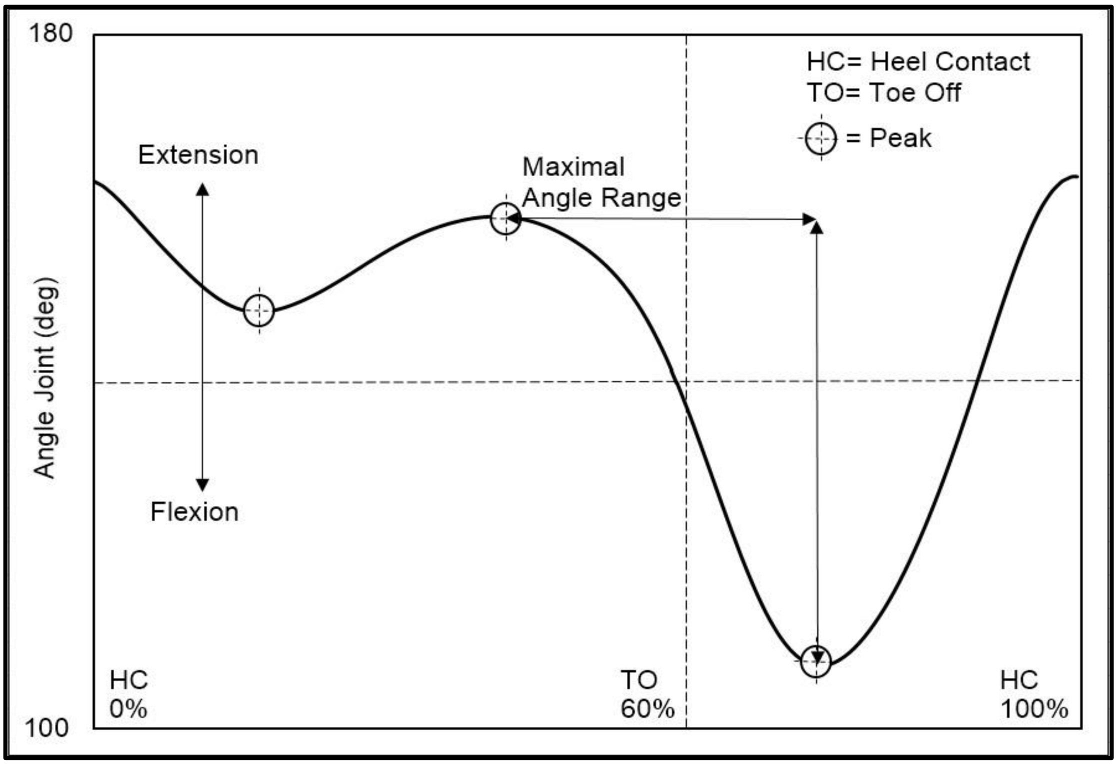

Figure 2.2 Knee joint angle

At the ankle joint, an increased angle indicated plantarflexion, while a decrease was taken to indicate dorsiflexion. The first peak plantarflexion angle was detected during the loading response phase, the second peak plantarflexion angle during the initial swing phase, the first peak dorsiflexion angle during the terminal stance phase, and the second peak dorsiflexion angle during the mid-swing phase. The maximal angle range was calculated from the second peak plantarflexion angle to the first peak dorsiflexion angle (Fig. 2.3).

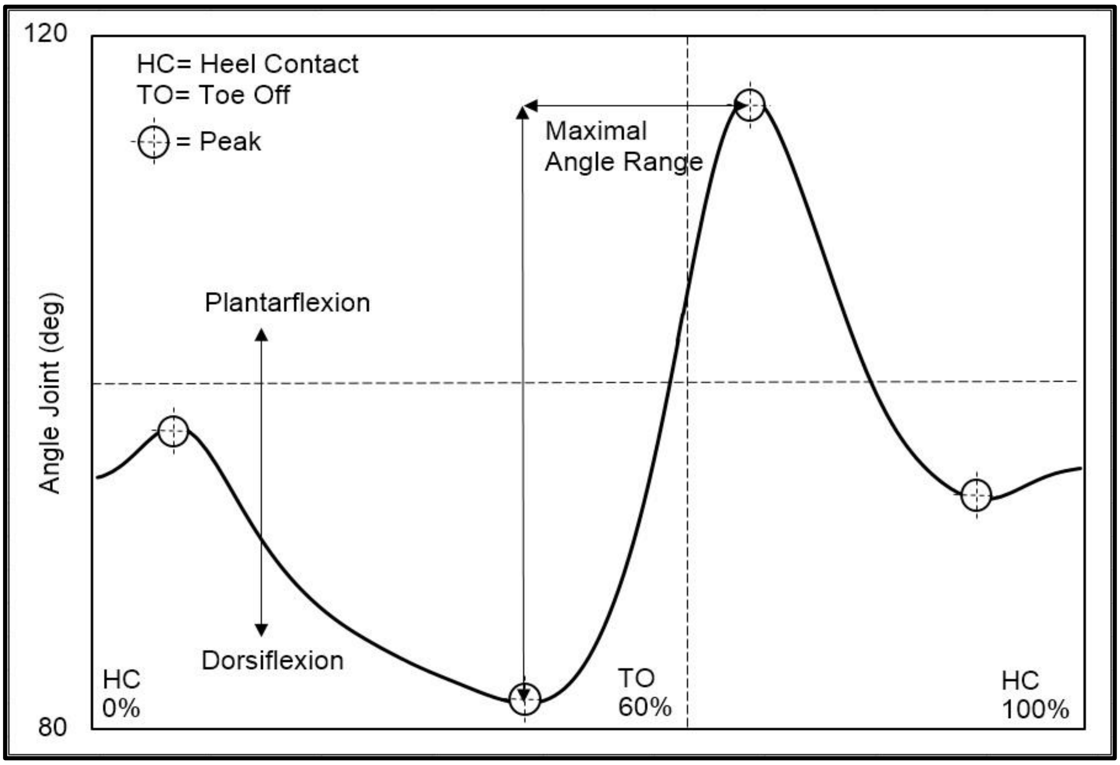

Figure 2.3 Ankle joint angle

For angular velocity parameters at the hip joint, a positive value indicated extension, while a negative value indicated flexion. The first peak extension angular velocity, second peak extension angular velocity, and peak flexion angular velocity were detected during the mid-stance phase, terminal swing phase, and initial swing phase, respectively (Fig. 2.4).

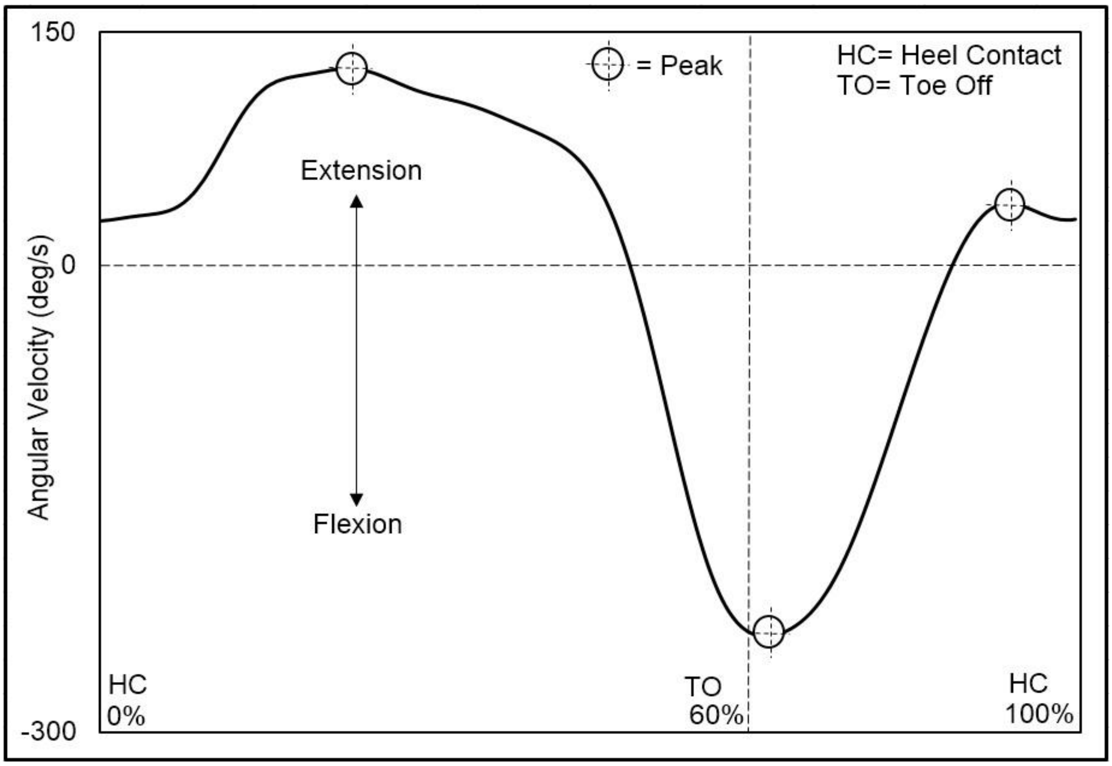

Figure 2.4 Hip angular velocity

For angular velocity parameters at the knee joint, a positive value indicated extension, while a negative value indicated flexion. The first peak extension angular velocity, second peak extension angular velocity, first peak flexion angular velocity, and second peak flexion angular velocity were detected during the mid-stance phase, terminal swing phase, loading response phase, and initial swing phase, respectively (Fig. 2.5).

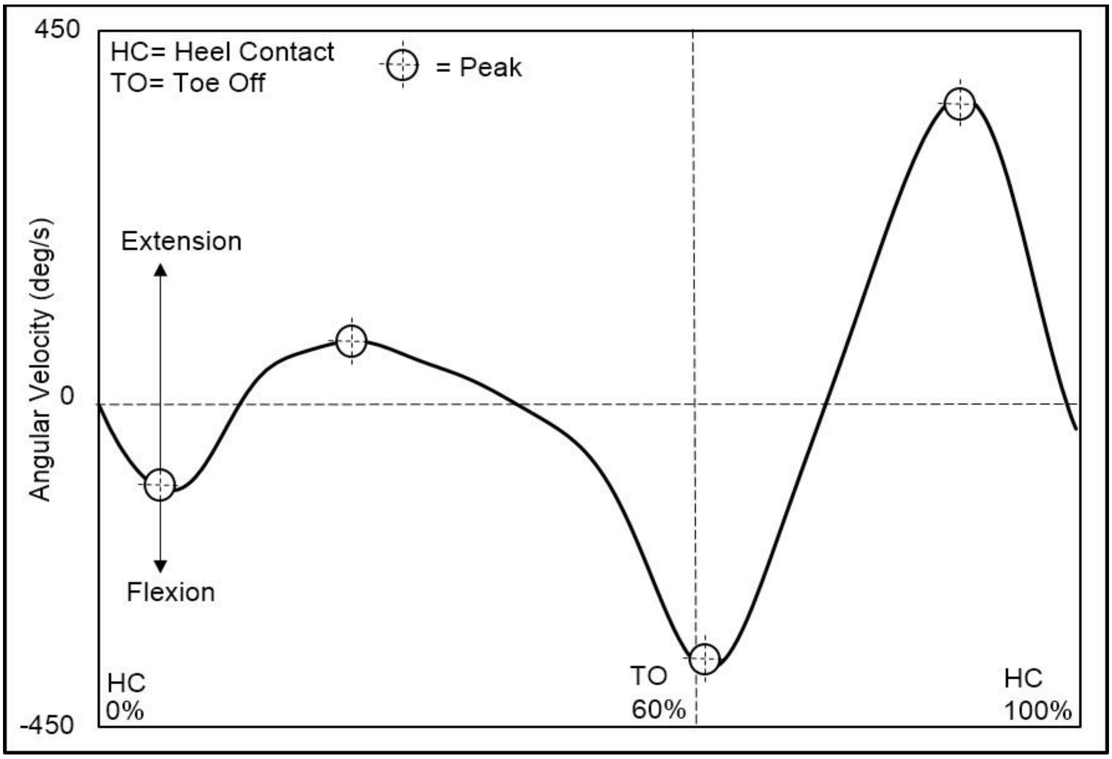

Figure 2.5 Knee angular velocity

Finally, at the ankle joint, a positive angular velocity value indicated plantarflexion, while a negative value indicated dorsiflexion. The first peak plantarflexion angular velocity, second peak plantarflexion angular velocity, first peak dorsiflexion angular velocity, and second peak angular velocity were detected during the pre-swing phase, terminal swing phase, loading response phase, and initial swing phase, respectively (Fig. 6).

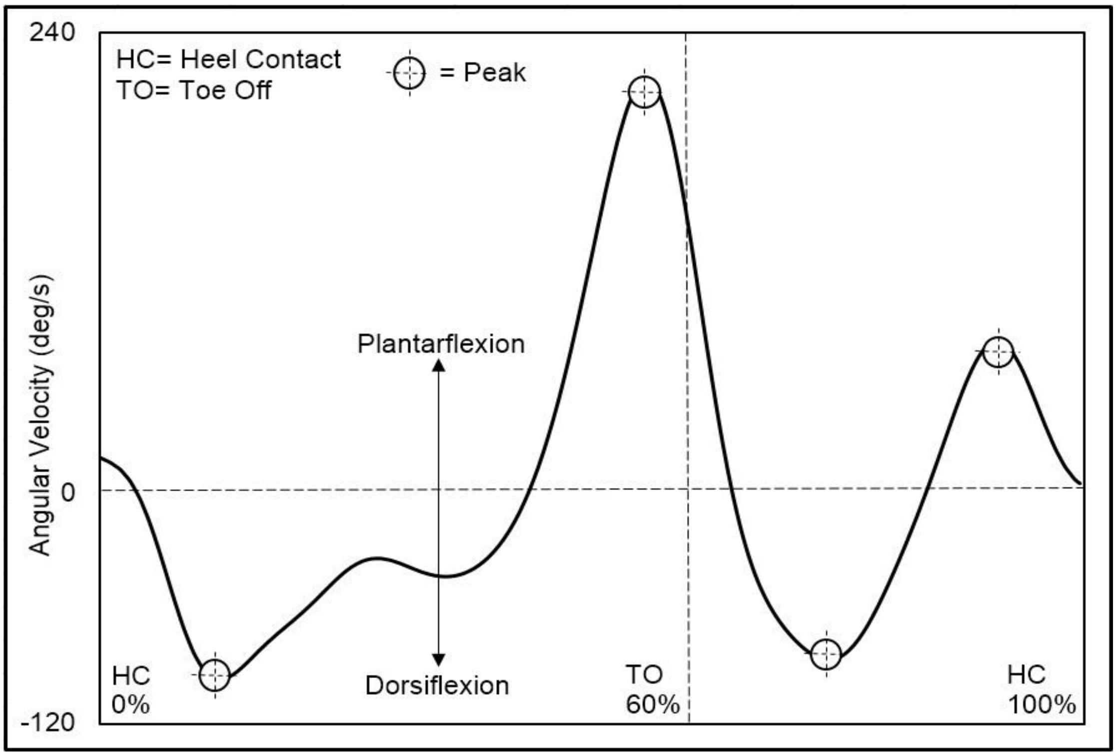

Figure 2.6 Ankle angular velocity

2.2.5. Statistical analysis

Statistical analysis was performed using IBM SPSS Version 21.0 (Chicago, USA). Descriptive results were presented as means and standard deviation. Unpaired *t*-tests were performed to analyse differences in participant characteristics and gait parameters between elderly and very elderly Japanese women. The effect size (Cohen's d) of parameters was calculated. The level of significance was set at 0.05.

2.3 Results

2.3.1 Participants

In the present study, the age of the very elderly women (group 2) was significantly greater than that of the elderly women (group 1) ($p < 0.01$). Furthermore, height and lower-limb length in group 2 were significantly smaller than those in Group 1 ($p < 0.01$, $p < 0.05$, respectively). However, no significant difference was found in body weight between the groups (Table 2.1).

2.3.2 Basic gait parameters

Basic gait parameters for the 2 groups are presented in Table 2.2. Group 2 exhibited a significantly slower walking speed ($p < 0.05$) and shorter stride length, right and left step lengths, and step length (all $p < 0.01$), than those observed in group 1. Furthermore, the walk ratio in group 2 was also significantly less than that of Group 1 ($p < 0.05$). However, no significant differences were found in the difference between right and step lengths, ratio of step length to height, ratio of step length to lower-limb length, or cadence.

Table 2.2 Comparison of basic gait parameters between elderly women and very elderly women

Parameters	Group 1 (Elderly women)	Group 2 (Very elderly women)	*p* value	Effect size
Walking speed *(m/min)*	75.3 ± 10.0	68.8 ± 8.1	< 0.05	0.71
Stride length (*cm*)	122.0 ± 11.5	112.5 ± 7.5	< 0.01	0.97
Step length *(cm)*	60.9 ± 5.7	55.9 ± 3.6	< 0.01	1.04
Ratio of step length to height	0.40 ± 0.04	0.38 ± 0.03	NS	0.56
Ratio of step length to lower-limb length	0.88 ± 0.08	0.84 ± 0.08	NS	0.50
Cadence *(steps/min)*	123.6 ± 10.5	122.5 ± 8.7	NS	0.11
Walk ratio	0.50 ± 0.06	0.46 ± 0.03	< 0.05	0.84

NS: Not significant. All values are presented as mean +/- standard deviation.

2.3.3 Gait cycle parameters

A comparison of gait cycle parameters between the 2 groups is presented in Table 3. Significant differences were observed in the percentage of total duration attributable to the swing and stance phases ($p < 0.05$). The swing phase percentage in group 2 was significantly smaller than that of Group 1 ($p < 0.05$). Conversely, the stance phase percentage in group 2 was significantly greater than that of group 1 ($p < 0.05$). However, there were no significant differences observed between the groups with respect to the durations of the swing phase, stance phase, duration of gait cycle, single support percentage, or double support percentage.

Table 2.3 Comparison of gait cycle parameters between elderly women and very elderly women

Parameters	Group 1 (Elderly women)	Group 2 (Very elderly women)	*p* value	Effect size
Duration of swing phase *(sec)*	0.38 ± 0.02	0.38 ± 0.02	NS	0.00
Duration of stance phase *(sec)*	0.59 ± 0.06	0.61 ± 0.05	NS	0.36
Duration of one gait cycle *(sec)*	0.98 ± 0.08	0.99 ± 0.07	NS	0.18
Swing phase percentage *(%)*	39.4 ± 1.3	38.6 ± 1.1	< 0.05	0.66
Stance phase percentage *(%)*	60.6 ± 1.3	61.4 ± 1.1	< 0.05	0.66
Single support percentage *(%)*	78.6 ± 2.6	77.2 ± 2.2	NS	0.58
Double support percentage *(%)*	21.4 ± 2.6	22.8 ± 2.2	NS	0.58

NS: Not significant. All values are presented as mean +/- standard deviation.

2.3.4 Joint angle parameters

Significant differences were observed in the peak extension timing of the hip joint, second peak flexion timing of the knee joint, and second peak plantarflexion timing of the ankle joint ($p < 0.05$, $p < 0.01$, and $p < 0.05$, respectively).

Table 4 shows the results of all joint angle parameters. At the hip joint, the peak extension timing in group 2 was significantly later than that observed in group 1 ($p < 0.05$). This observation was also true at the knee and ankle joints, with the second peak flexion ($p < 0.01$) and second peak plantarflexion ($p < 0.05$), respectively, occurring later in group 2 than in group 1. However, no other significant differences were noted with respect to joint angle parameters.

Table 2.4. Comparison of the joint angle parameters between elderly women and very elderly women

Parameters	Group 1 (Elderly women)	Group 2 (Very elderly women)	*p* value	Effect size
Hip Joint				
Peak extension angle *(deg)*	19.4 ± 4.0	18.4 ± 4.8	NS	0.22
Peak extension timing *(%)*	54.2 ± 1.2	54.9 ± 0.7	< 0.05	0.71
Peak flexion angle *(deg)*	-27.0 ± 2.6	-27.8 ± 2.4	NS	0.32
Peak flexion timing *(%)*	88.1 ± 1.8	88.9 ± 1.6	NS	0.47
Maximal angle range *(deg)*	46.4 ± 3.8	46.3 ± 4.4	NS	0.02
Knee Joint				
Peak extension angle *(deg)*	172.0 ± 5.4	170.1 ± 5.8	NS	0.34
Peak extension timing *(%)*	40.8 ± 3.2	42.0 ± 3.6	NS	0.35
First peak flexion angle *(deg)*	157.2 ± 6.0	156.6 ± 4.2	NS	0.11
First peak flexion timing *(%)*	13.4 ± 1.1	13.1 ± 1.8	NS	0.20
Second peak flexion angle *(deg)*	114.4 ± 5.2	115.3 ± 4.6	NS	0.18
Second peak flexion timing *(%)*	73.4 ± 1.1	74.3 ± 0.9	< 0.01	0.89
Maximal angle range *(deg)*	57.5 ± 4.5	54.8 ± 4.9	NS	0.57
Ankle Joint				
First peak plantarflexion angle *(deg)*	102.1 ± 4.7	101.9 ± 3.6	NS	0.48
First peak plantarflexion timing *(%)*	5.9 ± 1.3	5.4 ± 1.2	NS	0.40
Second peak plantarflexion angle *(deg)*	111.6 ± 5.7	111.4 ± 6.3	NS	0.03
Second peak plantarflexion timing *(%)*	63.9 ± 1.5	65.0 ± 1.5	< 0.05	0.73
First peak dorsiflexion angle *(deg)*	84.5 ± 4.3	84.4 ± 3.5	NS	0.02
First peak dorsiflexion timing *(%)*	41.6 ± 5.3	43.2 ± 3.5	NS	0.35
Second peak dorsiflexion angle *(deg)*	92.0 ± 5.0	92.4 ± 3.2	NS	0.09
Second peak dorsiflexion timing *(%)*	83.8 ± 2.4	84.7 ± 1.6	NS	0.44
Maximal angle range *(deg)*	27.1 ± 4.1	27.0 ± 4.2	NS	0.02

NS: Not significant. All values are presented as mean +/- standard deviation.

2.3.5 Angular velocity parameters

Table 5 shows the results of all angular velocity parameters. At the hip joint, the second peak extension timing and peak flexion timing in group 2 were significantly later than those in group 1 ($p < 0.05$). Again, this relationship held true for the knee and ankle joints; the second peak flexion timing at the knee ($p < 0.05$), and the first peak plantarflexion timing at the ankle ($p < 0.05$) were both later in group 2 than those observed in group 1. No significant differences were found in any other angular velocity parameters at the hip, knee, or ankle joints.

Table 2.5. Comparison of the angular velocity parameters between elderly women and very elderly women

Parameters	Group 1 (Elderly women)	Group 2 (Very elderly women)	*p* value	Effect size
Hip Joint				
First peak extension angular velocity *(deg/s)*	139.6 ± 26.2	129.5 ± 22.9	NS	0.41
First peak extension timing *(%)*	21.2 ± 2.9	20.3 ± 3.5	NS	0.28
Second peak extension angular velocity *(deg/s)*	43.1 ± 21.8	41.5 ± 17.2	NS	0.08
Second peak extension timing *(%)*	93.2 ± 2.7	94.7 ± 2.1	<0.05	0.62
Peak flexion velocity *(deg/s)*	-232.7 ± 29.5	-226.8 ± 39.7	NS	0.17
Peak flexion timing *(%)*	66.8 ± 1.6	67.8 ± 1.5	<0.05	0.64
Knee Joint				
First peak extension angular velocity *(deg/s)*	95.3 ± 27.5	87.0 ± 29.0	NS	0.29
First peak extension timing *(%)*	23.9 ± 3.1	23.1 ± 3.9	NS	0.23
Second peak extension angular velocity *(deg/s)*	403.6 ± 50.7	379.2 ± 55.4	NS	0.46
Second peak extension timing *(%)*	88.7 ± 1.1	89.0 ± 1.3	NS	0.25
First peak flexion angular velocity *(deg/s)*	-176.8 ± 47.7	-157.1 ± 38.6	NS	0.45
First peak flexion timing *(%)*	5.9 ± 1.3	6.0 ± 1.3	NS	0.07
Second peak flexion angular velocity *(deg/s)*	-400.1 ± 50.7	-378.0 ± 52.9	NS	0.42
Second peak flexion timing *(%)*	62.3 ± 1.1	63.2 ± 1.6	<0.05	0.65
Ankle Joint				
First peak plantarflexion angular velocity *(deg/s)*	275.2 ± 43.8	264.9 ± 44.9	NS	0.23
First peak plantarflexion timing *(%)*	57.3 ± 2.1	58.5 ± 1.5	<0.05	0.65
Second peak plantarflexion angular velocity *(deg/s)*	81.7 ± 23.8	87.7 ± 33.8	NS	0.66
Second peak plantarflexion timing *(%)*	91.8 ± 2.6	92.4 ± 2.7	NS	0.22
First peak dorsiflexion angular velocity *(deg/s)*	-111.1 ± 21.0	-104.4 ± 20.7	NS	0.32
First peak dorsiflexion timing *(%)*	12.0 ± 1.9	11.3 ± 1.6	NS	0.40
Second peak dorsiflexion angular velocity *(deg/s)*	-167.3 ± 41.9	-161.2 ± 52.0	NS	0.13
Second peak dorsiflexion timing *(%)*	71.3 ± 2.9	72.5 ± 2.4	NS	0.45

NS: Not significant. All values are presented as mean +/- standard deviation.

2.4 Discussion

2.4.1 Basic gait parameters

The key finding of this study is that a number of gait parameters are strongly associated with aging, as demonstrated in Japanese women across 2 subcategories (elderly and very elderly) in the 65 to 84 years age range. Slower walking speeds, shorter stride lengths, shorter step lengths, and a lower walk ratio were observed in the very elderly age group, when compared with elderly participants. Slower walking speeds in the elderly have been reported in many studies (Himann et al. 1988; Kaneko et al. 1991; Bohannon 1997; Prince et al. 1997; Callisaya et al. 2008). In this study, a decrease in the walking speed of the very elderly was primarily the product of a decrease in step/stride length; this observation has also been made in a number of previous studies (Bohannon 1997; Schulz 2012; Afiah et al. 2014b). Moreover, shorter step/stride length in very elderly women was largely associated with short stature. This observation is in agreement with those made by Bendall et al. (1989), Kimura et al. (2007), and Winter et al. (1990), where it was noted that height is directly related to stride length and walking speed. Furthermore, very elderly women showed lower walk ratios than their elderly counterparts. The walk ratio is a speed-independent indicator of walking patterns, and is derived from step length and cadence (Sekiya and Nagasaki 1998). Crosbie et al. (1997) found that gait variability in older adults is more likely to be step length-dependent, due to a limited gait capacity when compared to younger individuals. Therefore, the present study serves to extend observations made previously, in that lower walk ratios in very elderly women are indicative of a change in gait behaviour from a step length-dependent to cadence-dependent pattern; however, no significant differences were found with respect to cadence.

Furthermore, no significant differences were found in cadence between elderly and very elderly women. This finding is compatible with a number of previous studies, which reported that elderly individuals maintain a normal cadence during walking (Winter 1991; Watelain et al. 2000; Silder et al. 2008). Such observations are thought to be a product of generally high activity levels in elderly participants, and are aided by the absence of gait-related pathologies (Winter 1991). The elderly participants included in this study were also moderately active and had a reasonably good walking ability; therefore, it may be difficult to observe any significant difference with respect to cadence between elderly and very elderly women.

2.4.2 Gait cycle parameters

Importantly, when analysing the complete gait cycle, it was also observed that very elderly women exhibit a smaller percentage of swing phase and greater percentage of stance phase, when compared with the elderly group. The swing phase is characterised by progression of the swing limb between consecutive support positions, and constitutes the basis of forward movement (Winter et al. 1990; Mills and Barrett 2001). The swing phase begins immediately after toe-off, and is determined by swing limb advancement. The stance phase involves a period of bilateral foot contact with the floor (double stance phase) at the beginning and end of a gait cycle (Perry and Burnfield 2010). In the present study, the smaller percentages of swing phase noted in very elderly women may be a product of reductions in swing limb advancement and muscle power, while greater percentages of stance phase might be caused by diminished limb and trunk stability. These results are similar to those reported by Whittle (2007) and Perry and Burnfield (2010), whereby normal swing acceleration is decreased due to hip flexor weakness and slow limb advancement in the elderly. An increase in the duration of the stance phase was taken to indicate difficulty with maintaining balance while walking in elderly people. In addition, a greater percentage of stance indicated that the additional time after completing limb advancement was needed for elderly women for weight-bearing stability; however, it should be noted that no significant difference was found in the percentage duration of the double support phase. This result is analogous to that observed by Kimura et al. (2007), who found that a longer stance phase is a primary characteristic of the elderly, as a response to impaired balance during walking.

2.4.3 Joint angle parameters

It is well established that a number of joint angle movements are characteristic of the gait patterns observed in the elderly (Winter et al. 1990; Woollacott and Tang 1997; Kirkwood et al. 2007; Schmitz et al. 2009). The present study provides novel extension to those performed previously, by analysing essential joint angles at the hip, knee and ankle; specifically, the timing of peak angle throughout the gait cycle. In this study, both the peak angle and the temporal relationship of this value with the complete gait cycle were analysed as a means of improving understanding of gait characteristics in elderly Japanese women.

Interestingly, the only significant differences noted between elderly and very elderly women were related to the timing of peak joint angles; namely, the peak extension timing at the hip joint, second peak flexion timing at the knee joint, and second peak plantarflexion timing at the ankle joint.

No significant differences were found in the peak values of any joint angle between elderly and very elderly women, in the present study. This finding is discordant with a number of previous studies regarding the effect of aging on joint angle parameters. For instance, DeVita and Hortobagyi (2000) reported that joint angular kinematics at the hip, knee, and ankle joints significantly differed according to age. Similarly, Ko et al. (2010) identified decreases in range of motion at the hip and ankle joints, as well as a reduction in peak plantarflexion angle in elderly people. In contrast, a study from Mills and Barrett (2001) reported no differences in the peak value of any joint angle, and suggested that this may be a product of differences in gait speed or stride length, general health condition, and activity levels in elderly participants. In the present study, the lack of significant differences in joint angle measurements is likely due to consistency in cadence and the ratio of step length to lower-limb length between elderly and very elderly women. Moreover, previous differences in peak joint angle measurements have primarily been noted when comparing young and elderly age groups, rather than subsets of the elderly (Judge et al. 1996; Prince et al. 1997; Kerrigan et al. 1998; DeVita and Hortobagyi 2000). For instance, Kerrigan et al. (1998) pointed out that during comfortable walking, significant reductions were found in peak hip extension. Judge et al. (1996) also reported that older adults exhibit reduced peak ankle plantarflexion during the late stance phase, which constituted the primary contributing factor to shorter step lengths in the elderly, when compared to young participants.

When analysing the timing of peak joint angles, it was noted that delayed peak timing begun at approximately 54% of the gait cycle. At the hip joint, peak extension timing in very elderly women was delayed when compared to elderly women, and occurred during the pre-swing phase (50% to 62% of the gait cycle) when the hip joint transferred from a flexed to extended position. In this phase, terminal double limb support is initiated by floor contact of the contralateral limb (Perry and Burnfield 2010). A number of previous studies have identified gait characteristics of the hip joint in elderly individuals (Kerrigan et al. 1998; DeVita and Hortobagyi 2000; Schmitz et al. 2009; Anderson and Madigan 2014). For instance, Alcock et al. (2013) suggested that an extra increase in power generation at the hip is required during the pre-swing phase in elderly adults, due to a reduction in gait capacity. In addition, Kerrigan et al. (1998) reported that a reduction in peak hip extension angle during walking is associated with an increase in anterior pelvic tilt and a reduced range of motion in hip extension; these factors, prevalent in elderly individuals, may contribute to age-related differences in gait motion (Anderson and Madigan 2014). In keeping with studies performed by Kerrigan et al. (1998), Alcock et al. (2013), and Anderson and Madigan (2014), the delay in peak extension timing of the hip joint in very elderly women might be a reflection of several factors, such as the extra effort required to change the hip joint position, poor hip flexor power for push-off, and a reduction in the range of extension.

Delayed peak joint angle timing was also detected during the initial swing phase (62% to 75% of gait cycle). In this phase, delayed timing was noted when the knee and ankle joints transferred from extended to flexed and dorsiflexed to plantarflexed positions, respectively. The initial swing phase begins when the foot leaves the ground and continues until maximum knee flexion occurs (Perry and Burnfield 2010). Knee flexion is essential in lifting the foot for swing limb advancement and to facilitate foot clearance during the initial swing phase (Nene et al. 1999). Indeed, diminished knee flexion during the initial swing phase is associated with knee stiffness during walking (Goldberg et al. 2003). Moreover, elderly individuals appear to produce less isokinetic ankle plantarflexion during walking (Silder et al. 2008), have a more limited range of motion at the knee joint (Kirkwood et al. 2007), and exhibit poorer propulsion during the push-off period as a product of smaller plantarflexor torques (Cho et al. 2004). In addition, Ko et al. (2011) reported that elderly women exhibit poorer capacity to advance the swing limb forwards during the swing phase, as a product of less generative mechanical work expenditure from the knee joint. In a report from Shin et al. (2012), there was a significant correlation between muscle strength and gait variability at the knee joint. Accordingly, it can be suggested that the delayed peak angle timings observed during the initial swing phase at the knee and ankle joints are a product of knee stiffness, a reduction in push-off torque, less power to lift the limb, and deteriorating muscle strength with age.

It is also possible that delayed peak angle timings are affected by delays during the previous gait phase. For instance, the first delay in angular timing is observed at approximately 54% of the gait cycle; consequently, this may then affect peak angle timing in the subsequent phases (Fig. 2.7). However, delayed peak timing does not appear to continue from 76% until the end of the gait cycle. Accordingly, delays in peak angle timing are likely to primarily reflect unique joint behaviour in the very elderly.

2.4.4 Angular velocity parameters

To our knowledge, this study is the first to provide a comparison of elderly and very elderly women with respect to peak angular velocities, and the temporal relationship of these peak values to the gait cycle, at the hip, knee, and ankle joints. However, significant differences were only noted in the timing of peak values throughout the gait cycle, rather than the peak velocities themselves. Peak values occurred during the pre-swing phase, initial swing phase, and terminal swing phase. Previously identified significant differences in peak angular velocity parameters have primarily been observed in comparison with younger (Watelain et al. 2000; Mills and Barrett 2001; Anderson and Madigan 2014) and middle-age participants (Ko et al. 2012). If the timing of the peak joint angle parameter is representative of the timing of joint angle displacement, then the timing of the peak angular velocity is representative of the greatest moment of instantaneous change in flexion/extension. Therefore, in combination with the timing of peak joint angle movements, angular velocity is necessary to obtain a better understanding of gait characteristics in the elderly.

Delayed peak angular velocity begun in the pre-swing phase (52% to 62% of gait cycle), and was subsequently noted in the initial swing phase (62% to 75% of gait cycle) and terminal swing phase (87% to 100% of gait cycle). At the hip joint, the timing of the second peak extension in very elderly women occurred during the terminal swing phase (87 to 100% of gait cycle), which represents a delay when compared with elderly women. This corresponds to the point at which the hip joint is changing from a flexed to extended position. This phase is characterised by the deceleration of the swinging limb due to hip extensor activity (Rancho Los Amigos National Rehabilitation Center, 1989). During this phase, the hip maintains its earlier flexion (Kharb et al. 2011), while muscle action prepares the limb for stance by stopping further flexion (Perry and Burnfield 2010). During the terminal swing phase, limb retraction improves shock attenuation as a strategy to enhance foot ground-speed matching (Endo et al. 2014), and hamstring muscles rapidly increase the intensity of their action (Perry and Burnfield 2010). At the end of the terminal swing phase, however, activity of the hamstrings decreases, and the limb is optimally positioned for initial contact

(Perry and Burnfield 2010). Optimising the initial limb contact plays an important role in shock absorption. In the elderly, stride length is shortened as a means to compensate for a reduction in shock absorption capacity at the knee (Watelain et al. 2000). In addition, delayed and reduced hamstring muscle activation in the elderly is affected by the heel contact velocity (Prince et al. 1997; Lockhart and Kim 2006). Therefore, it is suggested that a delay in the timing of the peak hip angular velocity is related to a reduced necessity for shock absorption, due to a shorter stride length and/or slower adjustment of muscle activity at the hamstrings for shock absorption before heel contact in very elderly women.

Overall, findings in this study support the hypothesis that differences in gait appear between the subcategories of elderly and very elderly in Japanese women. Furthermore, a number of differences were noted in the timing of peak angle and angular velocity parameters between elderly and very elderly women. Interestingly, these peak timings appeared in the pre-swing, initial swing, and terminal swing phases (Fig.7), which are related to the position and advancement of the limb from its trailing position, toe clearance, and preparation for the next initial contact, respectively. Therefore, understanding joint angle and angular velocity parameters is essential to develop an understanding of aging-related changes in gait.

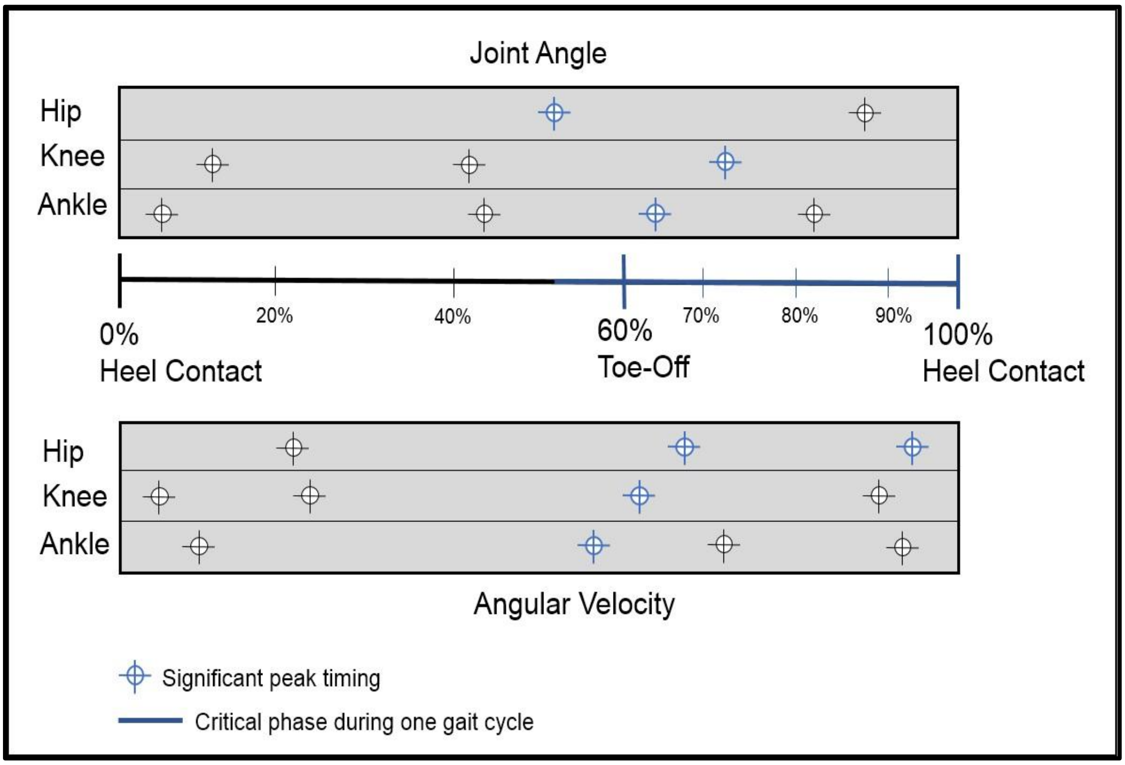

Figure 2.7 The peak timing of joint angle and angular velocity parameters

2.4.5 Implications, limitations, and future research

To our knowledge, gait parameters related to the peak timing of each joint angle movement and angular velocity have not previously been examined. Therefore, these findings may be useful as a means of identifying and monitoring parameters that are reflective of walking ability in the elderly population. A limitation of the present study was the inclusion of only elderly women subcategories. Therefore, in further investigation, it would be interesting to evaluate gait differences in elderly Japanese men.

2.5 Conclusions

This study investigated the effect of aging on gait parameters in elderly Japanese women. A number of parameters (walking speed, stride length, step length, walk ratio, swing phase percentage, stance phase percentage, and peak timing of joints angle and angular velocity) showed significant differences between elderly and very elderly women. Our results suggest that examining peak values and the timing of joint angle and angular velocity parameters at the hip, knee, and ankle joints are the best reflection of changes in gait with age.

Chapter 3

Age-related changes in the walking motion of elderly Japanese men

3.1 Introduction

Chapter 2 compared two subcategories of elderly Japanese women, elderly and very elderly, and suggested that gait characteristics of very elderly women include slower walking speed, shorter step and/or stride length, lower walk ratio, and changes in the percentage of the swing phase and stance phase. Additionally, elderly Japanese women also showed delayed peak timing of the joint angle and angular velocity at the hip, knee, and ankle joint. Therefore, according to Chapter 2, peak timing of the joint angle and angular velocity parameters could be used as reliable parameters to identify walking motions upon aging.

On the other hand, studies investigating walking patterns of elderly men are well documented (Murray et al. 1969; Kirtley et al. 1985; Judge et al. 1996; Watelain et al. 2000; Watanabe et al. 2015). For instance, Murray et al. (1969) and Kirtley et al. (1985) conducted the initial investigations of walking patterns of healthy old men. Their results indicated that both walking speed and stride length decreased with increasing age and that there was a correlation between cadence and knee flexion during the stance and swing phases. Moreover, Watelain et al. (2000) classified a gait pattern based on spatial-temporal parameters and muscle power. They concluded that peak muscle power at the hip, knee, and ankle joints of elderly men is lower compared with that of other age groups. Watanabe et al. (2015) also indicated that during one gait cycle, the toe-off timing in elderly men was late during their preferred walking speed in response to low activity of the rectus femoris muscle. Nevertheless, to our knowledge, there has been no investigation of the gait parameters that specifically reflect the walking motion of elderly men. The present study is an extension of the study described in Chapter 2; we investigated the gait characteristics of elderly Japanese men. Similarly, we aimed to identify reliable gait parameters to represent the walking motion of elderly Japanese men. Therefore, we investigated the effect of aging on gait parameters for elderly Japanese men to detect the parameters that reflect the walking motion upon aging in the Japanese population.

3.2 Material and methods

3.2.1 Participants

Fifty-three healthy elderly Japanese men were recruited and divided into two groups: Group 1, which comprised 33 elderly men (65–74.9 years old), and Group

2, which comprised 20 very elderly men (≥75 years old). In this study, one left-leg-dominant participant was included in each group and all other participants were right-leg-dominant. Participant characteristics are detailed in Table 3.1. Before the measurements, all participants were screened using a medical questionnaire (as described in Chapter 2). This study was approved by the Ethics Committee of the Faculty of Design at Kyushu University and written consent was obtained.

Table 3.1 Participant characteristics

	Group 1 (Elderly men)	Group 2 (Very elderly men)	*p* value
Age *(years)*	70.2 ± 2.7	77.1 ± 1.8	< 0.01
Body Height *(cm)*	164.8 ± 5.4	163.4 ± 4.8	NS
Body Weight *(kg)*	62.4 ± 6.4	61.5 ± 7.7	NS
Lower-Limb Length *(cm)*	74.2 ± 3.8	73.5 ± 3.9	NS

NS: Not significant. All values are presented as mean +/- standard deviation.

3.2.2 Procedures

In this chapter, a 3D motion analysis system and a Cortex software program (Motion Analysis Corporation, Santa Rosa, CA, USA) were used (the same systems were used in Chapter 2). Participants were required to wear clothes that were in firm contact with the skin. Thirty-one trajectory markers and the main segment of each participant’s body, as described in Chapter 2, were used in this study.

3.2.3 Measurements

Participants were asked to walk barefoot on a flat surface for 10 meters at a speed that they selected for themselves. Participants were also instructed to practice walking barefoot before the measurements. Three self-selected speed measurements were recorded for each participant.

3.2.4 Gait parameters

Gait parameters described in Chapter 2 and KineAnalyzer software (Kissei Comtec, Nagano, Japan) were used to analyze the elderly Japanese men.

3.2.5 Statistical analysis

Statistical analysis was performed using IBM SPSS version 21.0 for Windows (Chicago, IL, USA). Descriptive results were presented as means and standard deviation. Unpaired *t*-test was performed to analyze the differences in characteristics and gait parameters between elderly Japanese men and very elderly Japanese men. The effect size (Cohen's d) of parameters was calculated. The level of significance was set at 0.05.

3.3 Results

3.3.1 Participants

The age of the very elderly men (group 2) was significantly older than that of the elderly men (group 1) (p < 0.01). However, no significant differences were found for body height, body weight, and lower-limb length between groups (Table 3.1).

3.3.2 Basic gait parameters

The results of all basic gait parameters are presented in Table 3.2. Group 2 showed slower walking speeds and slower cadence than group 1 (p<0.05 and p<0.01). However, no significant differences were found in step length, stride length, ratio of step length to height, ratio of step length to lower-limb length, and walk ratio.

Table 3.2. Comparison of the basic gait parameters between elderly men and very elderly men

Parameters	Group 1 (Elderly men)	Group 2 (Very elderly men)	*p* value	Effect size
Walking speed *(m/min)*	73.9 ± 8.9	67.9 ± 10.1	<0.05	0.48
Stride length (cm)	125.6 ± 11.5	122.2 ± 15.2	NS	0.25
Step length (cm)	62.7 ± 5.8	61.1 ± 7.5	NS	0.24
Ratio of step length to height	0.38 ± 0.03	0.37 ± 0.04	NS	0.28
Ratio of step length to lower-limb length	0.85 ± 0.07	0.83 ± 0.09	NS	0.25
Cadence *(steps/min)*	117.6 ± 6.8	111.4 ± 7.8	<0.01	0.85
Walk ratio	0.53 ± 0.05	0.55 ± 0.07	NS	0.33

NS: Not significant. All values are presented as mean +/- standard deviation.

3.3.3 Gait cycle parameters

Table 3.3 shows the results of all gait cycle parameters. All gait cycle parameters were significantly different between the two groups ($p < 0.05$ and $p < 0.01$). Duration of the swing phase, duration of the stance phase, and duration of one gait cycle for group 2 were significantly greater than those for group 1 ($p < 0.05$ and $p < 0.01$). Moreover, the swing phase percentage and single support percentage for group 2 were significantly lower than those for Group 1 ($p < 0.05$); however, the percentage of the stance phase and the double support percentage for group 2 were significantly greater than those for Group 1 ($p < 0.05$).

Table 3.3. Comparison of the gait cycle parameters between elderly men and very elderly men

Parameters	Group 1 (Elderly men)	Group 2 (Very elderly men)	*p* value	Effect size
Duration of swing phase *(sec)*	0.40 ± 0.02	0.42 ± 0.03	< 0.05	0.78
Duration of stance phase *(sec)*	0.62 ± 0.05	0.66 ± 0.05	< 0.01	0.80
Duration of one gait cycle *(sec)*	1.02 ± 0.06	1.08 ± 0.08	< 0.01	0.85
Swing phase percentage *(%)*	39.6 ± 1.4	38.7 ± 1.4	< 0.05	0.64
Stance phase percentage *(%)*	60.4 ± 1.4	61.3 ± 1.4	< 0.05	0.64
Single support percentage *(%)*	79.0 ± 2.6	77.4 ± 2.8	< 0.05	0.60
Double support percentage *(%)*	21.0 ± 2.6	22.6 ± 2.8	< 0.05	0.59

NS: Not significant. All values are presented as mean +/- standard deviation.

3.3.4 Joint angle parameters

The results of all joint angle parameters are presented in Table 3.4. Significant differences were found only for peak extension timing at the hip joint and peak extension timing at the knee joint ($p < 0.05$). At the hip and knee joints, the peak extension timing of group 2 was significantly later compared with that of group 1 ($p < 0.05$). However, no significant differences between group 1 and group 2 were found for ankle joint parameters.

Table 3.4. Comparison of the joint angle parameters between elderly men and very elderly men

Parameters	Group 1 (Elderly men)	Group 2 (Very elderly men)	*p* value	Effect size
Hip Joint				
Peak extension angle *(deg)*	17.6 ± 5.8	18.8 ± 4.9	NS	0.22
Peak extension timing *(%)*	53.5 ± 1.1	54.3 ± 1.2	< 0.05	0.69
Peak flexion angle *(deg)*	-26.8 ± 5.3	-24.6 ± 4.8	NS	0.47
Peak flexion timing *(%)*	88.0 ± 1.7	88.1 ± 2.1	NS	0.05
Maximal angle range *(deg)*	44.4 ± 4.1	43.5 ± 5.9	NS	0.18
Knee Joint				
Peak extension angle *(deg)*	171.5 ± 6.3	173.0 ± 6.2	NS	0.24
Peak extension timing *(%)*	40.3 ± 2.6	42.5 ± 4.1	< 0.05	0.64
First peak flexion angle *(deg)*	155.8 ± 7.1	157.0 ± 7.3	NS	0.17
First peak flexion timing *(%)*	13.0 ± 1.0	13.1 ± 2.0	NS	0.06
Second peak flexion angle *(deg)*	114.0 ± 7.1	116.5 ± 7.0	NS	0.35
Second peak flexion timing *(%)*	72.7 ± 2.3	73.1 ± 2.7	NS	0.16
Maximal angle range *(deg)*	57.5 ± 4.1	58.7 ± 5.0	NS	0.26
Ankle Joint				
First peak plantarflexion angle *(deg)*	103.0 ± 3.0	103.3 ± 3.2	NS	0.97
First peak plantarflexion timing *(%)*	5.8 ± 1.2	5.5 ± 1.1	NS	0.26
Second peak plantarflexion angle *(deg)*	111.0 ± 4.8	108.4 ± 6.1	NS	0.47
Second peak plantarflexion timing *(%)*	64.7 ± 1.7	65.4 ± 2.7	NS	0.31
First peak dorsiflexion angle *(deg)*	86.0 ± 3.3	85.2 ± 4.6	NS	0.20
First peak dorsiflexion timing *(%)*	45.2 ± 5.0	45.8 ± 5.8	NS	0.11
Second peak dorsiflexion angle *(deg)*	94.9 ± 3.3	93.0 ± 4.7	NS	0.47
Second peak dorsiflexion timing *(%)*	84.9 ± 2.6	84.2 ± 2.5	NS	0.27
Maximal angle range *(deg)*	25.0 ± 3.8	23.2 ± 3.6	NS	0.49

NS: Not significant. All values are presented as mean +/- standard deviation.

3.3.5 Angular velocity parameters

Table 3.5 shows the results of all angular velocity parameters. In this study, significant differences were only found for the first and second peaks of the plantarflexion angular velocity at the ankle joint ($p < 0.05$). The first peak plantarflexion angular velocity for Group 2 was significantly lower compared with that for Group 1 ($p < 0.05$), and the second peak plantarflexion angular velocity for Group 2 was significantly greater compared with that for Group 1 ($p < 0.05$). However, no significant differences were found for other angular velocity parameters of the hip and knee joints.

Table 3.5. Comparison of the angular velocity parameters between elderly men and very elderly men

Parameters	Group 1 (Elderly men)	Group 2 (Very elderly men)	*p* value	Effect size
Hip Joint				
First peak extension angular velocity *(deg/s)*	126.7 ± 18.9	117.4 ± 20.8	NS	0.47
First peak extension timing *(%)*	22.2 ± 3.4	21.9 ± 5.7	NS	0.64
Second peak extension angular velocity *(deg/s)*	42.4 ± 18.7	36.0 ± 15.7	NS	0.37
Second peak extension timing *(%)*	93.2 ± 1.4	92.8 ± 2.0	NS	0.23
Peak flexion angular velocity *(deg/s)*	-211.8 ± 28.1	-195.3 ± 27.4	NS	0.59
Peak flexion timing *(%)*	65.2 ± 1.4	65.8 ± 1.5	NS	0.41
Knee Joint				
First peak extension angular velocity *(deg/s)*	91.9 ± 23.5	82.8 ± 28.6	NS	0.35
First peak extension timing *(%)*	23.9 ± 2.6	23.4 ± 4.2	NS	0.14
Second peak extension angular velocity *(deg/s)*	386.6 ± 49.4	374.9 ± 54.7	NS	0.22
Second peak extension timing *(%)*	89.0 ± 2.5	89.4 ± 1.1	NS	0.20
First peak flexion angular velocity *(deg/s)*	-183.0 ± 44.8	-190.6 ± 49.0	NS	0.16
First peak flexion timing *(%)*	5.2 ± 1.0	5.0 ± 0.9	NS	0.21
Second peak flexion angular velocity *(deg/s)*	-379.1 ± 42.2	-355.0 ± 44.9	NS	0.55
Second peak flexion timing *(%)*	62.1 ± 1.6	63.0 ± 3.3	NS	0.35
Ankle Joint				
First peak plantarflexion angular velocity *(deg/s)*	257.0 ± 34.4	235.6 ± 34.8	<0.05	0.87
First peak plantarflexion timing *(%)*	57.8 ± 1.8	58.3 ± 2.3	NS	0.24
Second peak plantarflexion angular velocity *(deg/s)*	58.9 ± 24.3	76.7 ± 25.7	<0.05	0.71
Second peak plantarflexion timing *(%)*	91.6 ± 3.3	91.1 ± 2.1	NS	0.18
First peak dorsiflexion angular velocity *(deg/s)*	-95.8 ± 16.9	-96.7 ± 21.6	NS	0.05
First peak dorsiflexion timing *(%)*	12.1 ± 4.0	12.9 ± 5.1	NS	0.17
Second peak dorsiflexion angular velocity *(deg/s)*	-125.7 ± 33.4	-120.1 ± 19.7	NS	0.20
Second peak dorsiflexion timing *(%)*	71.6 ± 2.0	72.4 ± 2.1	NS	0.39

NS: Not significant. All values are presented as mean +/- standard deviation.

3.4 Discussion

3.4.1 Basic gait parameters

The present study investigated the effect of aging on gait parameters in elderly Japanese men. Slower walking speeds and slower cadence were observed in very elderly men when compared with elderly men. Slower walking speed and changes in the cadence of elderly participants have been found in many previous studies of gait motion (Andriacchi et al. 1977; Kirtley et al. 1985; Friedman 1988; Prince et al. 1997; Watelain et al. 2000; Cho et al. 2004; Anderson and Madigan 2014; Jerome et al. 2015). In this study, slower walking speed was primarily affected by slower cadence and shorter stride length of very elderly men, although no significant differences were found in stride length between the two groups. Additionally, this finding is similar to that reported by Winter et al. (1990); gait in the elderly can be characterized by reduced walking speed, decreased cadence, and shorter stride length.

3.4.2 Gait cycle parameters

Furthermore, significant results were also found for the single support percentage and the double support percentage between elderly men and very elderly men. The very elderly men showed a lower single support percentage and greater double support percentage compared with elderly men. The single support phase was related to the swing phase of the other limb (Ayyappa 1997), whereas the double support phase included the duration of both feet making contact with the floor (Demura et al. 2012). The body's center of mass moves forward from the supporting limb and toward the anticipated landing position of the swing limb (Frank and Patla 2003). The body is in an inherent state of instability during single limb support (Prince et al. 1997), and elderly people reduce the concentric energy output of trunk muscles to minimize the energy transferred to the trunk due to less stability during the single support phase (McGibbon and Krebs 2001). A lower single support percentage might be apparent in very elderly men because of instability during single limb support. In addition, the lower single support percentage was also affected by the longer duration of the stance phase in very elderly men throughout the gait cycle. However, very elderly men showed a greater percentage during the double support phase compared with elderly men. Increased double limb support occurs with gait alteration in elderly people (Alexander 1996; Liu et al. 2006). In addition, McGibbon and Krebs (2001) showed that during the double support phase, elderly people rely more on eccentric control of low-back muscles to regulate energy transfer during the double limb support phase. Additionally, in this study, very elderly men also showed shorter swing phase duration compared with elderly men. Therefore, the greater percentage of the double support phase in the present study indicated that very elderly men spent more time with both feet on the floor than did elderly men to maintain their walking stability after complete swing limb advancement.

3.4.3 Joint angle parameters

The peak value and peak timing of joint angle parameters for elderly Japanese men were investigated to develop an understanding of their gait characteristics. This study showed no significant differences in the peak values of any joint angle in elderly and very elderly men. Furthermore, significant differences were only found for peak timings of joint angle parameters, namely peak extension timing at the hip and knee joint.

When analyzing the timing of joint angles, it was noted that delayed peak timing began at approximately 40% of the gait cycle. At the hip joint, peak extension timing in very elderly men was delayed when compared to that of elderly men, and it occurred during the terminal stance phase (31% to 50% of the gait cycle) when the hip joint transferred from a flexed to an extended position. At the knee joint, peak timing occurred during the terminal stance phase (31% to 50% of the gait cycle), whereas peak timing at the hip joint occurred during the pre-swing phase (50% to 62% of the gait cycle) when the joints transferred their position from flexed to extended.

The terminal stance phase begins with heel rise and continues until the other foot strikes the ground (Perry and Burnfield 2010). During this phase, the body is propelled forward until the pre-swing is started (Rueterbories et al. 2010). Generally, the knee joint dynamics are associated with the neuromuscular activation pattern during walking, such as lower range of motion in the knee or moderate levels of knee osteoarthritis (Mundermann et al. 2005; Astephen Wilson et al. 2011). Furthermore, knee extension strength decreased during the stance phase, and elderly people also reduced their ankle plantarflexion to maintain greater foot–floor contact during the terminal stance phase as a result of the change in dynamic stiffness during walking (Kerrigan et al. 1998). Elderly people made more intentional efforts to achieve more propulsion energy for forceful joint extension. Moreover, the knee adduction moment during the terminal stance phase contributed to the change in the medial-to-lateral distribution of proximal tibial bone mineral density, and variability of knee joint movements during the terminal stance phase is one of the essential parameters during walking (Thorp et al. 2006). In addition, muscle activities during the terminal stance phase such as of the tibialis anterior, bicep femoris, medial hamstring, and vastus lateralis decreased as gait speed decreased (Schmitz et al. 2009). Therefore, delayed peak timing during knee joint extension during the terminal stance phase in the present study might have been affected by the very elderly men making more of an effort to transfer the knee joint from the flexed position to the extended position due to decreased knee extension strength, less bone mineral density, and decreased muscle power during the terminal stance phase. Additionally, delayed peak timing during this phase is also affected by slow walking speed in very elderly men compared with elderly men.

Delayed peak joint angle timing was also detected during the pre-swing phase (50% to 62% of the gait cycle). During this phase, delayed timing was noted when the hip joint transferred from the flexed to the extended position. As previously discussed in Chapter 2, delayed peak joint angle timing at the hip joint during this phase might be a reflection of the extra effort required to change the hip joint position, poor hip flexor power for push-off, and reduction in the range of extension.

For elderly Japanese men, the delayed peak timing might also be affected by delayed peak timing during the previous gait phase. However, delayed peak timing did not appear until approximately 64% of the gait cycle (Fig. 3.1). Therefore, as previously discussed in Chapter 2, the observed delayed peak timing would be mainly reflected by the unique joint angle behavior during the gait phase in very elderly men.

3.4.4 Angular velocity parameters

In Chapter 2, significant differences were found only during peak timing of angular velocity parameters of elderly and very elderly women. The findings of the present study show the significant differences for elderly Japanese men, particularly the peak values of angular velocity at the ankle joint. Some previous studies have indicated several essential findings regarding angular velocity in the gait of the elderly (Mills and Barrett 2001; Van Iersel et al. 2007; Silder et al. 2008; Leung et al. 2014). For instance, Van Iersel et al. (2007) showed that an increased value in angular velocity was associated with an increased risk of falling. However, Mills and Barrett (2001) found no significant differences in the peak value of angular velocity between younger and older adults due to the low variability in the preferred gait velocity and stride length. Therefore, this study extends the previous studies by combining the understanding of the peak value of angular velocity and the phase of the gait cycle when the peak value of each joint occurs, although no significant differences were found in peak timing parameters.

The present study shows that the first peak plantarflexion angular velocity at the ankle joint of very elderly men is significantly lower compared with elderly men, as detected during the pre-swing phase. The pre-swing phase is a very complex part of the gait cycle for the ankle joint because the ankle movements are related to progression and body weight is rapidly transferred from the trailing limb to the forward limb (Perry and Burnfield 2010). The plantar flexors have a crucial role in mobility, whereas the triceps surae muscle architecture and Achilles tendon stiffness are associated with better mobility performance (Stenroth et al. 2015). Less power in the ankle plantar flexor affects the reduction of the walking speed (Norris et al. 2007), and older adults showed decreased plantarflexion muscle force due to less strength and ankle plasticity (Hortobágyi et al. 2016). Additionally, elderly people showed less isometric strength in ankle plantarflexion

(Graham et al. 2015), and variability in ankle plantarflexion affects gait velocity, step length, and cadence in healthy elderly individuals (Leung et al. 2014). Therefore, lower peak plantarflexion angular velocity at the ankle joint might be affected by less ankle plantar flexor power and the reduction in plantarflexion muscle activity during the pre-swing phase. In addition, lower peak plantarflexion angular velocity is strongly affected by slower cadence in very elderly men compared with elderly men.

However, second peak plantarflexion angular velocity at the ankle joint of very elderly men was greater compared with that of elderly men. This peak value occurred during the terminal swing phase and is known as the final phase during one gait cycle. During this phase, pretibial muscle action increases to ensure that the ankle will be neutral for optimum heel contact during the next phase (Perry and Burnfield 2010). Endo and Herr (2014) simulated ankle mechanical impedance in humans with time-varying ankle parameters. Their findings showed that the tibialis anterior increased during the terminal swing phase before heel-strike and that increased impedance before heel-stride may prepare the body for shock absorption before entering the loading response phase. In addition, the ankle joint is an essential joint for propulsion and shock absorption at the maximum plantarflexion moment (Lee et al. 2013)

Accordingly, greater peak plantarflexion angular velocity in very elderly men might be affected by the increased muscle power for shock absorption during the terminal swing phase and by the effort to transfer the ankle joint from the dorsiflexed to the plantarflexed position.

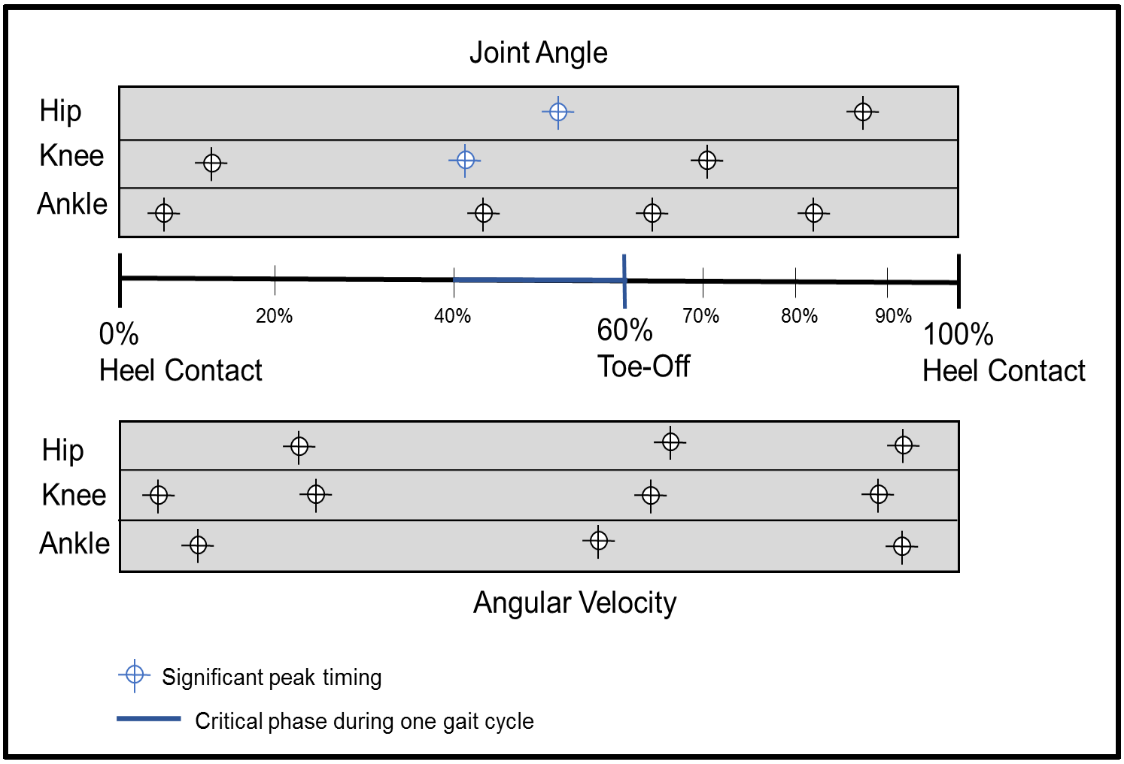

Figure 3.1 The peak timing of joint angle and angular velocity parameters

3.4.4 Implications, limitations, and future research

The novel aspect in this study is the detailed investigation of both the joint angle and angular velocity to provide a new understanding of peak value and peak timing parameters. Peak value and peak timing in the joint angle and angular velocity are gait parameters that strongly affect walking motion upon aging in elderly Japanese men. One limitation of this study is that the comparison is limited to elderly men. The results might have been different if the participants were elderly women and elderly men. Therefore, it would be very useful to evaluate gait differences between elderly Japanese women and men during future research.

3.5 Conclusion

The results of the present study show the differences in some gait parameters (basic gait, gait cycle, joint angle, and angular velocity) between elderly men and very elderly men. Peak timing of joint angle parameters and peak value of angular velocity parameters could be reliable parameters for reflecting the walking motion upon aging in elderly Japanese men.

Chapter 4

Sex-specific differences in walking motion for healthy, elderly Japanese individuals

4.1 Introduction

Chapter 3 compared two subcategories of elderly Japanese men. Very elderly men had slower walking speed, slower cadence, longer duration of one gait cycle, lower single support percentages, and higher double support percentages. In addition, very elderly men showed delayed peak timing of the joint angle and angular velocity at the hip and knee joint. New gait parameters were proposed in Chapters 2 and 3, namely the peak values and temporal relationship of these peaks with the gait cycle at the hip and knee joints. These new parameters could be useful as a means of identifying and monitoring parameters that are reflective of walking ability in an elderly population. The findings of Chapters 2 and 3 also suggest that assessment of gait characteristics is essential to prevent deterioration of walking ability with advanced age.

In addition to aging factors, walking ability is also influenced by the differences between sexes (Whittle 2007). In general, men have larger bone areas than women, which is consistent with their larger body size (Riggs et al. 2004), and differences in skeletal dimensions lead to differences in walking patterns (Cho et al. 2004). Furthermore, the ability to support the body with one leg decreased with advanced age; older women stepped with the inferior leg muscle due to deterioration in body mass (Demura et al. 2008). In addition, differences in other physical factors between men and women could contribute to specific walking patterns (Hachisuka et al. 1998; Daigle 2003; Chung and Wang 2010). Accordingly, investigations regarding sex-specific differences in gait parameters could provide new insight for characterizing gait in an elderly population.

Prior studies have addressed the differences in gait characteristics between men and women, but these studies compared only young and middle-aged/older adults (Cho et al. 2004; Chiu and Wang 2007; Mazzà et al. 2009; Ko et al. 2010; Bruening et al. 2015; El-Ashker et al. 2015). For instance, Cho et al. (2004) and Ko et al. (2011) indicated that younger and older women tend to walk with shorter stride lengths and slower walking speeds than men due to the shorter heights of women. Bruening et al. (2015) also found that adult women walked with greater pelvic transverse plane and torso rotation. Cho et al. (2004) reported that stance durations and double support phases were not different between younger men and women. Few studies have addressed differences in gait characteristics according to sex-specific differences in elderly people. However, those that did used middle-aged and elderly people to classify these differences (Boyer et al. 2008; Ko et al. 2011). Elderly participants with disabilities in physical function and participants with a history of lower-limb arthritis and Parkinson disease were involved in such studies (Hachisuka et al. 1998; Callisaya et al. 2008), and gait parameters were limited only to spatial-temporal parameters (Callisaya et al. 2008). Accordingly, it is necessary to extend prior investigations regarding sex-specific differences in gait with advanced age by including new peak values and timing parameters observed in Chapters 2 and 3.

The present study aimed to investigate differences in gait parameters according to sex in healthy, elderly Japanese individuals and to identify specific gait characteristics of elderly men and women.

4.2 Material and methods

4.2.1 Participants

Data were collected from 102 elderly Japanese individuals and divided into two categories: elderly men (53 individuals) and elderly women (49 individuals). Participant characteristics are detailed in Table 4.1. Before the measurements, all participants were screened using a medical questionnaire (same as used in Chapters 2 and 3). This study was approved by the Ethics Committee of the Faculty of Design at Kyushu University and written consent was obtained.

Table 4.1 Participant characteristics

	Elderly men	Elderly women	*p* value
Age *(years)*	72.8 ± 4.1	73.5 ± 4.7	NS
Body Height *(cm)*	164.3 ± 5.2	151.0 ± 5.7	< 0.01
Body Weight *(kg)*	62.1 ± 6.9	49.7 ± 8.1	< 0.01
Lower-Limb Length *(cm)*	74.0 ± 3.8	68.5 ± 3.5	< 0.01

NS: Not significant. All values are presented as mean +/- standard deviation.

4.2.2 Procedures

A 3D motion analysis system (same system used in Chapter 2) and a Cortex software program (Motion Analysis Corporation, Santa Rosa, CA, USA) were used. Participants were required to wear clothes that were in firm contact with the skin. Thirty-three trajectory markers and the main segment of each participant's body were the same as that used in Chapters 2 and 3.

4.2.3 Measurements

Participants were asked to walk barefoot on a flat surface for 10 meters at a speed that they selected themselves. Participants were also instructed to practice walking barefoot before the measurements. Three self-selected speed measurements were recorded for each participant.

4.2.4 Gait Parameters

Gait parameters used in Chapters 2 and 3 and KineAnalyzer software (Kissei Comtec, Nagano, Japan) were used to analyze the differences between elderly women and men.

4.2.5 Statistical Analysis

Statistical analysis was performed using IBM SPSS version 21.0 for Windows (Chicago, IL, USA). Descriptive results are presented as means and standard deviation. Unpaired *t*-test was performed to analyze the differences in participant characteristics and gait parameters of elderly women and elderly men. The effect size (Cohen's d) of parameters was calculated. The level of significance was set at 0.05.

4.3 Results

4.3.1 Participants

In this study, body height, body weight, and lower-limb length of elderly men were significantly greater than that of elderly women ($p < 0.01$). However, no significant differences based on age were found between sexes (Table 4.1).

4.3.2 Basic gait parameters

Basic gait parameters for elderly men and women are presented in Table 4.2. Elderly women had significantly shorter stride ($p < 0.05$) and step lengths, faster cadence, and lower walk ratio (all $p < 0.01$) than that observed for elderly men. However, no significant differences were found in walking speed, ratio of step length to height, or ratio of step length to lower-limb length.

Table 4.2. Comparison of the basic gait parameters between elderly men and women

Parameters	Elderly men	Elderly women	*p* value	Effect size
Walking speed *(m/min)*	71.6 ± 9.7	72.8 ± 9.8	NS	0.12
Stride length *(cm)*	124.3 ± 13.0	118.3 ± 11.1	< 0.05	0.50
Step length *(cm)*	62.1 ± 6.4	58.9 ± 5.5	< 0.01	0.54
Ratio of step length to height	0.38 ± 0.04	0.39 ± 0.04	NS	0.25
Ratio of step length to lower-limb length	0.84 ± 0.08	0.86 ± 0.08	NS	0.25
Cadence *(steps/min)*	115.3 ± 7.7	123.2 ± 9.7	< 0.01	0.90
Walk ratio	0.54 ± 0.06	0.48 ± 0.05	< 0.01	1.09

NS: Not significant. All values are presented as mean +/- standard deviation.

4.3.3 Gait cycle parameters

A comparison of gait cycle parameters between elderly men and women is presented in Table 4.3. Significant differences were observed in the duration of the swing phase, duration of the stance phase, and duration of one gait cycle (all $p < 0.01$). Duration for elderly women was significantly less than that for elderly men. However, there were no significant differences observed between elderly men and women regarding the swing phase percentage, stance phase percentage, single support percentage, or double support percentage.

Table 4.3. Comparison of the gait cycle parameters between elderly men and women

Parameters	Elderly men	Elderly women	*p* value	Effect size
Duration of swing phase *(sec)*	0.41 ± 0.02	0.38 ± 0.02	< 0.01	0.50
Duration of stance phase *(sec)*	0.64 ± 0.05	0.60 ± 0.06	< 0.01	0.72
Duration of one gait cycle *(sec)*	1.05 ± 0.07	0.98 ± 0.08	< 0.01	1.06
Swing phase percentage *(%)*	39.2 ± 1.4	39.1 ± 1.3	NS	0.07
Stance phase percentage *(%)*	60.8 ± 1.4	60.9 ± 1.3	NS	0.07
Single support percentage *(%)*	78.4 ± 2.8	78.1 ± 2.5	NS	0.11
Double support percentage *(%)*	21.6 ± 2.8	21.9 ± 2.5	NS	0.11

NS: Not significant. All values are presented as mean +/- standard deviation.

4.3.4 Joint angle parameters

Table 4.4 shows the results of all joint angle parameters. At the hip joint, the peak extension timing for elderly women was significantly later than that observed for elderly men ($p < 0.01$), and the maximal angle range for elderly women was greater than that for elderly men ($p < 0.05$). At the knee joint, the second peak flexion timing of elderly women was also significantly later than that of elderly men ($p < 0.05$). At the ankle joint, the first peak dorsiflexion timing for elderly women was significantly earlier than that for elderly men ($p < 0.01$), and the second peak dorsiflexion angle for elderly women was smaller than that for elderly men ($p < 0.05$). The maximal angle range for elderly women was significantly greater than that for men ($p < 0.01$).

Table 4.4. Comparison of the joint angle parameters between elderly men and women

Parameters	Elderly men	Elderly women	*p* value	Effect size
Hip Joint				
Peak extension angle *(deg)*	18.1 ± 5.5	19.0 ± 4.3	NS	0.18
Peak extension timing *(%)*	53.8 ± 1.2	54.5 ± 1.1	< 0.01	0.60
Peak flexion angle *(deg)*	-26.0 ± 5.2	-27.3 ± 2.5	NS	0.31
Peak flexion timing *(%)*	88.0 ± 1.8	88.4 ± 1.7	NS	0.23
Maximal angle range *(deg)*	44.1 ± 4.8	46.3 ± 4.0	< 0.05	0.50
Knee Joint				
Peak extension angle *(deg)*	172.1 ± 6.2	171.2 ± 5.6	NS	0.15
Peak extension timing *(%)*	41.1 ± 3.4	41.3 ± 3.4	NS	0.06
First peak flexion angle *(deg)*	156.3 ± 7.1	157.0 ± 5.3	NS	0.11
First peak flexion timing *(%)*	13.1 ± 1.4	13.3 ± 1.4	NS	0.14
Second peak flexion angle *(deg)*	115.0 ± 7.1	114.7 ± 4.9	NS	0.50
Second peak flexion timing *(%)*	72.9 ± 2.4	73.7 ± 1.1	< 0.05	0.54
Maximal angle range *(deg)*	57.9 ± 4.5	56.5 ± 4.8	NS	0.30
Ankle Joint				
First peak plantarflexion angle *(deg)*	103.1 ± 3.0	102.1 ± 4.3	NS	0.27
First peak plantarflexion timing *(%)*	5.7 ± 1.2	5.7 ± 1.3	NS	0.00
Second peak plantarflexion angle *(deg)*	110.0 ± 5.4	111.5 ± 5.9	NS	0.26
Second peak plantarflexion timing *(%)*	64.9 ± 2.1	64.3 ± 1.6	NS	0.32
First peak dorsiflexion angle *(deg)*	85.7 ± 3.8	84.5 ± 4.0	NS	0.30
First peak dorsiflexion timing *(%)*	45.5 ± 5.3	42.2 ± 4.7	< 0.01	0.66
Second peak dorsiflexion angle *(deg)*	94.2 ± 4.0	92.1 ± 4.3	< 0.05	0.50
Second peak dorsiflexion timing *(%)*	84.7 ± 2.6	84.1 ± 2.2	NS	0.25
Maximal angle range *(deg)*	24.3 ± 3.8	27.0 ± 4.1	< 0.01	0.68

NS: Not significant. All values are presented as mean +/- standard deviation.

4.3.5 Angular velocity parameters

Table 4.5 shows the results of all angular velocity parameters. At the hip joint, the first peak extension and peak flexion angular velocities for elderly women were significantly greater than those for elderly men, and the peak flexion timing for elderly women was significantly later than that for elderly men (all $p < 0.01$). Similarly, at the knee joint, the first peak flexion timing for elderly women was significantly later than that for elderly men ($p < 0.05$). Finally, at the ankle joint, significant differences were only found in the peak value of angular velocity parameters, the first and second peaks of plantarflexion angular velocities, and the first and second peaks of dorsiflexion angular velocities; however, the angular velocities for elderly women were greater than those for elderly men (all $p < 0.01$).

Table 4.5. Comparison of the angular velocity parameters between elderly men and women

Parameters	Elderly men	Elderly women	*p* value	Effect size
Hip Joint				
First peak extension angular velocity *(deg/s)*	123.2 ± 20.0	135.7 ± 25.2	< 0.01	0.50
First peak extension timing *(%)*	22.1 ± 4.4	20.8 ± 3.1	NS	0.34
Second peak extension angular velocity *(deg/s)*	40.0 ± 17.8	42.5 ± 20.0	NS	0.13
Second peak extension timing *(%)*	93.0 ± 1.7	93.8 ± 2.6	NS	0.36
Peak flexion angular velocity *(deg/s)*	-205.5 ± 28.7	-230.4 ± 33.5	< 0.01	0.80
Peak flexion timing *(%)*	65.4 ± 1.5	67.1 ± 1.6	< 0.01	1.10
Knee Joint				
First peak extension angular velocity *(deg/s)*	88.5 ± 25.7	92.1 ± 28.1	NS	0.13
First peak extension timing *(%)*	23.7 ± 3.3	23.6 ± 3.4	NS	0.30
Second peak extension angular velocity *(deg/s)*	382.2 ± 51.3	394.2 ± 53.4	NS	0.23
Second peak extension timing *(%)*	89.2 ± 2.1	88.8 ± 1.2	NS	0.23
First peak flexion angular velocity *(deg/s)*	-185.8 ± 46.1	-169.2 ± 45.0	NS	0.36
First peak flexion timing *(%)*	5.1 ± 1.0	5.9 ± 1.3	< 0.01	0.69
Second peak flexion angular velocity *(deg/s)*	-370.0 ± 44.4	-391.5 ± 52.1	< 0.05	0.44
Second peak flexion timing *(%)*	62.4 ± 2.4	62.6 ± 1.4	NS	0.10
Ankle Joint				
First peak plantarflexion angular velocity *(deg/s)*	248.9 ± 35.8	271.2 ± 44.0	< 0.01	0.55
First peak plantarflexion timing *(%)*	58.0 ± 2.0	57.8 ± 1.9	NS	010
Second peak plantarflexion angular velocity *(deg/s)*	65.6 ± 26.1	84.0 ± 27.9	< 0.01	0.68
Second peak plantarflexion timing *(%)*	91.4 ± 2.9	92.0 ± 2.6	NS	0.22
First peak dorsiflexion angular velocity *(deg/s)*	-96.1 ± 18.6	-108.5 ± 20.9	< 0.01	0.63
First peak dorsiflexion timing *(%)*	12.4 ± 4.4	11.7 ± 1.8	NS	0.21
Second peak dorsiflexion angular velocity *(deg/s)*	-123.6 ± 28.9	-165.0 ± 45.7	< 0.01	1.08
Second peak dorsiflexion timing *(%)*	71.9 ± 2.1	71.8 ± 2.8	NS	0.04

NS: Not significant. All values are presented as mean +/- standard deviation.

4.4 Discussion

4.4.1 Basic gait parameters

In the present study, shorter stride and step lengths were observed for elderly women than for elderly men. These findings are consistent with previous studies of sex-specific differences in basic gait parameters, indicating that young or older women had shorter step/stride lengths than their male counterparts (Cho et al. 2004; Callisaya et al. 2008; Ko et al. 2011; Frimenko and Whitehead 2014; Bruening et al. 2015). For instance, Cho et al. (2004), Ko et al. (2011), and Bruening et al. (2015) reported that short step/stride length for younger and older women can be directly related to their anthropometric differences (such as short body height or leg length). Moreover, Frimenko and Whitehead (2014) defined step length as generally height-dependent. Accordingly, the differences in anthropometric characteristics, such as body height, lower-limb length, and ratio of step length to height, may cause short stride and step lengths in elderly women, although there were no significant differences in the ratio of step length to height.

Other notable findings in this study are that elderly women showed faster cadence and a lower walk ratio than did elderly men. Irrespective of age, sex-specific differences for cadence have been reported by many previous studies indicating that younger or older women walked with a faster cadence than their male counterparts (Cho et al. 2004; Callisaya et al. 2008; Boyer et al. 2008; Ko et al. 2011; Frimenko and Whitehead 2014; Bruening et al. 2015). As previously reported (Ko et al. 2011; Bruening et al. 2015; Di Nardo et al. 2015), young women walked with a faster cadence to walk at a similar speed as men and also to compensate for their shorter body height, as described in the previous paragraph. Therefore, it could be that faster cadence is a general phenomenon in the majority of women. Accordingly, faster cadence in elderly women might not be a sex-specific difference for gait with advanced age.

Furthermore, elderly women also showed a lower walk ratio than did elderly men. In contrast, Sekiya and Nagasaki (1998) reported that walk ratio did not differ between younger men and women. Crosbie et al. (1997) reported that gait variability in the elderly is more likely to be step length–dependent; however, this phenomenon is not imperceptible with respect to sex-specific differences. Terrier and Reynard (2015) reported no sex-specific differences in walk ratio among younger and middle-aged groups. Importantly, walking patterns of elderly individuals could be characterized by a consistent decrease in the walk ratio due to shorter step lengths (Sekiya and Nagasaki 1998). In addition, as previously discussed in Chapter 2, aging causes gait behavior to change from a step length–dependent pattern to a cadence-dependent pattern in elderly women. Accordingly, sex-specific differences in the walk ratio could be considered unusual for elderly individuals.

4.4.2 Gait cycle parameters

When analyzing the complete gait cycle, it was observed that elderly women exhibit shorter durations during the swing phase, stance phase, and one gait cycle than elderly men; this is mainly caused by the faster cadence of elderly women. However, there were no significant differences in swing and stance percentages or in single support and double support percentages. These findings are similar to those reported by Cho et al. (2004) and Ko et al. (2011), who indicated that younger and older women had a faster cadence than did men, which led to the shorter stance phase and duration of the gait cycle.

4.4.3 Joint angle parameters

For joint angle parameters, sex-specific differences in the peak angle joint were only found at the ankle joint, namely the second peak dorsiflexion angle. Interestingly, with respect to peak timing parameters, sex-specific differences were found for all leg joints. Delayed peak timing occurs at approximately 53%, 73%, and 42% of the gait cycle, namely during the pre-swing, initial swing, and terminal stance phases at the hip, knee, and ankle joints, respectively.

In this study, elderly women exhibited a greater hip maximal angle range than elderly men. In contrast, this difference did not appear among younger and adult individuals (Kernozek et al. 2007; Bruening et al. 2015). As reported (Boyer et al. 2008; Cho et al. 2004), among younger individuals, women had greater external hip extension and hip joint flexion than did men due to the greater anterior pelvic tilt. The internal rotation for adult women also increased, which was related to their wider pelvis and greater femoral anteversion than adult men (Kernozek et al. 2007; Bruening et al. 2015). Thus, the greater maximal angle range at the hip joint of elderly women could be one gait characteristic specific to sex irrespective of age.

At the same joint, elderly women exhibited delayed peak extension timing during the pre-swing phase (50% to 62% of gait cycle) when the hip joint transferred from flexion to extension. As previously discussed in Chapter 2, delayed peak timing observed during the pre-swing phase at the hip joint in elderly women might be due to the extra effort to change the hip joint position, poor hip flexor power for push-off, and the reduction in the range of extension. In addition, older women with a wide range of ages showed concentric effort of the hip flexor muscles during the pre-swing phase (Alcock et al. 2013). Accordingly, sex-specific differences in peak extension timing at the hip joint are unusual during old age.

At the knee joint, elderly women showed delayed peak flexion timing during the initial swing phase (62% to 75% of the gait cycle). This peak timing occurred when the knee movement was transferred from extension to flexion. Generally, gait variability was associated with muscle strength at the knee joint (Roppolo et al. 2012), whereas knee flexion was essential for lifting the foot for swing limb advancement and for facilitating foot clearance during the initial swing phase (Nene et al. 1999). Sex-specific differences were found in knee movement, as shown in the longer knee flexion of older women as a result of the early onset of knee flexion (Ko et al. 2011). Therefore, delay in the second peak flexion timing of the knee joint in elderly women might be a reflection of the extra effort to change the knee joint position, deterioration of muscle strength in elderly women, and early onset of knee flexion.

Finally, at the ankle joint, elderly women exhibit a significantly greater maximal angle range than do elderly men. Several studies of sex-specific differences have discussed that younger, adult, and older women have a greater ankle range of motion (ROM) than men (Decker et al. 2003; Kernozek et al. 2007; Boyer et al.

2008; Ko et al. 2011; Frimenko and Whitehead 2014; Bruening et al. 2015). For instance, Ko et al. (2011) reported that older women rely more on ankle angular motion during walking. Younger women also exhibit greater ankle ROM for absorbing energy of the ground, reducing the overall load transmitted to the knee, and maintaining the effectiveness of knee kinematics (Kernozek et al. 2007; Bruening et al. 2015). Accordingly, it can be suggested that a greater maximal angle range in elderly women might be a reflection of several factors. Importantly, this phenomenon is also indicated among younger and older individuals; therefore, sex-specific differences in ankle maximal angle range could not be categorized as a unique gait characteristic of elderly men and women.

4.4.4 Angular velocity parameters

Regarding angular velocity parameters, peak angular velocities in all joints had greater values in elderly women than in elderly men. These greater peak values are likely to be an instinctive effect due to the faster cadence of elderly women during walking. The joint angular velocity is associated with the dynamics of muscle activities, cadence, and velocity of forward progression (Granata et al. 2000). Faster cadence requires various muscle activities in the lower extremities (Shono et al. 2007). In addition, faster cadence coupled with greater mechanical energy absorption at the leg joints would affect the dynamics of muscle activities during walking (Ko et al. 2011). According to Granata et al. (2000), Shono et al. (2007), and Ko et al. (2011), faster cadence in elderly women caused greater peak angular velocities than in elderly men, which indicated greater muscle activities in the lower extremities and greater mechanical energy absorption during walking.

The delayed timing of the peak flexion angular velocity occurred during the loading response phase (2% to 12% of the gait cycle) when the knee joint movement transferred from extension to flexion. During this phase, the knee flexion position serves as a shock absorber while also maintaining stability during walking (Perry and Burnfield 2010). Furthermore, knee flexion was also a strategy for the soft landing technique throughout one gait cycle (Devita and Skelly 1992). Among younger individuals, women seemed to put forth more effort for knee joint movement and indicated less impact on the ground due to less contraction of the knee flexor compared to their male counterparts (Cho et al. 2004). Accordingly, it can be suggested that delays in the timing of the peak flexion angular velocity at the knee joint might be related to the extra effort to transfer the knee joint and used as a strategy for the soft landing technique.

Other notable delayed peak timing was also found for peak flexion angular velocity at the hip joint. This peak value occurred during the initial swing phase (62% to 75% of the gait cycle). In general, older women had greater anterior pelvic tilt (Boyer et al. 2008) and walked with greater adduction angles at the hip (Cho et al. 2004). In addition, adult women also exhibited greater hip adduction angular velocity due to more frontal negative work of the hip (Ferber et al. 2003). Therefore, the differences in peak flexion timing at the hip joint between elderly men and women are considered to be related to these aforementioned factors.

4.4.5 Implications, limitations, and future research

To our knowledge, differences according to sex in gait parameters related to the peak timing of each joint angle and angular velocity have not been previously investigated. These current findings may be useful to enhance the understanding of differences according to sex in gait characteristics, especially with respect to an elderly population. One potential limitation of the present study is that angular acceleration parameters were not observed. Therefore, further investigation should consider peak angular acceleration and its peak timing at the hip, knee, and ankle joints.

4.5 Conclusions

This study investigated differences according to sex in gait characteristics between elderly Japanese men and women. A number of parameters (stride/step length, cadence, walk ratio, duration of one gait cycle, hip and ankle maximal angle ranges, and peak value and its timing for joint angles and angular velocity) showed significant differences between elderly men and elderly women. It can be concluded that sex-specific differences such as lower walk ratio, greater hip maximal angle range, delayed peak extension timing at the hip joint, and delayed second peak flexion timing at the knee joint are unusual for elderly individuals. Additionally, specific gait motions in elderly women also could be identified using delayed peak timing of the peak flexion angular velocities at the hip and knee joints throughout one gait cycle.

Chapter 5

General discussions

5.1 Summary

The objectives of this dissertation were to investigate the effect of aging on gait parameters in Japanese elderly, to clarify whether age-related changes of gait characteristics are consistent and continue with advanced age when subcategorizing according to early and late elderly, and to investigate sex differences in gait characteristics between elderly Japanese men and women.

The first study (Chapter 2) identified the parameters that were reflective of gait characteristics in the elderly Japanese women. The elderly Japanese women were classified in two subcategories, namely elderly and very elderly, in order to represent the elderly at early and late age. The findings of this study highlighted that the very elderly women indicated a cadence-dependent walking pattern and showed delayed timings of the peak joint angles that begun at approximately 54% of the gait cycle at the hip joint. During pre-swing, initial swing, and terminal swing phases, very elderly women showed several delayed timings of the peak angle and peak angular velocity compared to elderly women. These delayed timings occurred at the hip, knee, and the ankle joints.

The second study (Chapter 3) was an extension of the study presented in Chapter 2 and investigated the reliable gait parameters to represent the walking motion among elderly Japanese men. The specific gait characteristics of the very elderly men were the slower walking speed, smaller cadence, delayed peak timing at the hip and knee joint, smaller first peak plantar flexion angular velocity, and greater second peak plantar flexion angular velocity at the ankle joint.

In the third study (Chapter 4), an investigation of sex-specific differences in gait parameters of Japanese elderly were conducted to identify the specific gait characteristics in elderly men and women. This study found that sex-specific differences in walk ratio, the maximal hip angle range, peak extension timing at the hip joint, and second peak flexion timing at the knee joint were peculiar to the elderly individuals.

5.2 General discussions

5.2.1 Gait characteristics in advanced age

The main goal of this dissertation was to provide new insight of age-related changes in walking motion in elderly Japanese women and men. Separately, Chapter 2 and 3 investigated age-related changes in walking motion in elderly Japanese women and elderly Japanese men, respectively. First, Chapter 2 was focused on identifying the reflective parameters of gait characteristics in the elderly population and hypothesized that differences in gait would exist between elderly and very elderly women. In this Chapter, new timing-related parameters for evaluating age-related changes in gait were proposed, namely, the timing of joint angle and angular velocity peak values throughout the gait cycle. The results of this Chapter demonstrated that very elderly women walked with slower walking speed, shorter step/stride length, and smaller walk ratio than elderly women. The lower walk ratios in very elderly women were indicative of a change in gait behavior from a step length-dependent to cadence-dependent gait pattern. Additionally, very elderly women also exhibit several delayed peak joint angle timings and peak angular velocity at the hip, knee, and ankle joints. The findings in this chapter support the hypothesis that the differences in gait do exist between the subcategories of elderly and very elderly Japanese women. These delayed timings are likely to primarily reflect unique joint behavior in the very elderly.

In the Chapter 2 and 3, significant differences were found between the peak joint angle timing and angular velocity parameters. Interestingly, the peak value of each leg joints did not show any significant differences. Generally, physical and physiological factors can contribute to the individual differences in gait performance among different age groups (Chung and Wang, 2010). For instance, the elderly participants walked with the similar motor task due to their physiological limits in torque and power production during gait that decreased by aging (DeVita and Hortobagyi, 2000). Mills and Barrett (2001) also suggested that many factors, such as differences in gait speed or stride length, general health condition, and activity levels in the elderly participants, could affect the significance of the peak value of joint movement. Meanwhile, the peak timing parameters in the present study were modified according to the gait cycle, which decreased the influence of the individual differences in the cadence and step length. Therefore, the lack of significant differences in the joint angle measurements were affected by the individual differences, such as the consistency in cadence and the ratio of step length to lower-limb length among the participants.

In order to reflect better the gait parameters that specifically show the walking motion among elderly, Chapter 3 extends the investigation of the previous Chapter by examining the gait characteristics of the elderly Japanese men. For basic gait and gait cycle parameters, gait characteristics among elderly men could be identified from the reduction in walking speed, the decrease in cadence, the smaller single support percentage, and greater double support percentage. With respect to the joint angle and the angular velocity parameters, specific gait characteristics of elderly Japanese men also could be identified from delayed peak extension timing at the hip and knee joint, smaller first peak plantar flexion angular velocity, and greater second peak plantar flexion angular velocity at the ankle joint.

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5.2.2 Sex-specific differences with advanced age

Table 5.1 shows the detailed findings of sex-specific differences in advanced age. In this dissertation, Chapter 2 and Chapter 3 identified specific gait characteristics both in elderly Japanese women and in men. Importantly, in order to be more specific about sex- differences in aging of gait motion, the final study (Chapter 4) observed sex-specific differences among elderly aged 65–85 years. While the majority of previous studies were more interested in sex-specific differences in gait motion in both younger and older adults (Cho et al., 2004; Boyer et al., 2008; Bruening et al., 2015), this dissertation focused on identification of the unusual gait characteristics with respect to the sex differences in advanced age.

Table 5.1 Sex-specific differences with advanced age

Chapter 2 and Chapter 3	Chapter 4 (Elderly men vs. Elderly women)
1. Same aging effect ▪ Slow walking speed ▪ Low swing phase percentage ▪ High stance phase percentage ▪ Delayed peak extension timing at the hip joint	**Specific gait characteristics of sex-differences with advanced age** ▪ Lower walk ratio in elderly women ▪ Delayed peak extension timing at the hip joint in elderly women ▪ Delayed peak flexion timing at the knee joint in elderly women ▪ Greater hip maximal angle range in elderly women
2. Different aging effect present only in elderly women ▪ Short step/stride length ▪ Low walk ratio ▪ Delayed peak flexion timing at the knee joint ▪ Delayed peak flexion/extension timing of angular velocity at the knee joint ▪ Delayed peak plantar flexion timing of angular velocity at the ankle joint	**Substantial gait parameters differences between elderly men and elderly women** ▪ Lower walk ratio in elderly women ▪ Delayed peak extension timing at the hip joint in elderly women
3. Different aging effect present only in elderly men ▪ High cadence ▪ Low single support percentage ▪ High double support percentage ▪ Delayed peak extension timing at the knee joint ▪ Low first peak plantar flexion angular velocity at the ankle joint ▪ High second peak plantar flexion angular velocity at the ankle joint	**General gait characteristics of sex-specific differences** ▪ Shorter step/stride length in elderly women ▪ Faster cadence in elderly women ▪ Greater ankle maximal angle range in elderly women

—— Common parameters between sex-specific differences in Chapters 2-3 and Chapter 4

Table 5.1 shows sex-specific differences between the Chapters 2 and 3 and indicate that the walking speed and the swing phase percentage decreased, while the stance phase percentage increased with age in both sexes. Similarly, delayed peak extension timing at the hip joint occurred in both very elderly women and men. Furthermore, only elderly women showed significant reduction in step/stride length and walk ratio, whilst elderly men showed significant differences in the duration of cadence, swing/stance phase percentage, and single support/double support percentage. Elderly women exhibited a significant difference in peak flexion timing at the knee joint, while the significant difference in the peak extension timing was only found in elderly men. With respect to angular velocity parameters, only elderly women showed significant differences in peak extension/flexion timing at the hip joint, peak flexion timing at the knee joint, and peak plantar flexion timing at the ankle joint. Meanwhile, elderly men showed significant differences in peak values of plantar flexion angular velocities at the ankle joint.

With respect to sex-specific differences in gait characteristics, several parameters such as shorter stride length, higher cadence, and greater maximal angle range at the ankle joint, were a general phenomenon in the majority of women and often reported among younger and/or older individuals. Therefore, these phenomena might not represent sex-specific differences in gait among individuals with advanced age. Regarding the angular velocity parameters, sex-specific differences in the timing of peak flexion angular velocities at the knee joint and hip joint could be considered unusual in elderly individuals. In addition, elderly women showed greater peak angular velocities of all leg joints that were likely to be an instinctive effect of higher cadence during walking in elderly women.

Importantly, two parameters presented in Chapters 2 and 3, namely walk ratio and peak extension timing at the hip joint, were found significantly different according to sex-specific gait characteristics with advanced age (Chapter 4). In this chapter, elderly women indicated a cadence-dependent pattern due to their lower walk ratio compared to elderly men. The sex-specific difference between elderly men and women was also found in the peak extension timing at the hip joint as the reflection of several gait factors, such as the extra effort required to change the hip joint position, poor hip flexor for push-off, and a reduction in the range of extension. Accordingly, walk ratio and peak extension timing at the hip joint were characterized as the very specific gait characteristics related to sex differences irrespective of age.

5.3 Implications

The findings of this dissertation have implications policy for the quality improvement of the health care system, as well as for the old age and social protection system. As aging is a global issue, new timing-related parameters that were proposed and the understanding of elderly and very elderly individuals gait characteristics would be necessary either for wellbeing or for the nursing, prevention from deterioration of walking ability, and rehabilitation of the motor disorders. Our research is in line with Franz (2016), that presented some rehabilitation approaches to improve the walking performance in aging population, such as resistance training or the hip flexor stretching to increase the flexibility gains, and Achilles tendon investigation to maintain mechanical performance of the plantar flexor muscles in old age. In addition, sex-specific differences could be considered when identifying specific gait characteristics among elderly populations over 65 years.

5.4 Limitations

Our knowledge regarding the gait characteristics among elderly Japanese and gait parameters that are reflective of walking ability in the elderly individuals was expanded based on this research. In addition, this study reports new insights in the biomechanics and gait analysis field. However, some limitations should be considered. First, the study included only elderly subcategories of participants and lacked a young or middle-aged comparison. When elderly participants were compared with younger or middle-aged participants, more reliable parameters were obtained (Chung and Wang, 2010; Ko et al., 2011; Alcock et al., 2013; Terrier and Reynard, 2015) Second, angular acceleration parameters were not analyzed. Therefore, several parameters did not show differences in two subcategories of Japanese elderly and in the sex-specific differences analysis.

5.5 Future research priorities

In the future, more subcategories of participants should be involved, especially more middle-aged participants, to evaluate the gait differences across a wider age range. Additionally, the peak angular velocities and the temporal relationship of these peak values with the gait cycle, at the hip, knee, and the ankle joints are also necessary in order to investigate gait characteristics in the elderly population.

5.6 Conclusions

This dissertation establishes the new timing-related parameters with respect to the joint angle and angular velocity at the hip, knee, and ankle joints. In order to identify specific gait characteristics among Japanese elderly, several important points have been suggested. First, delays in peak timing of the joint angle and the angular velocity parameters were shown in the very elderly category, both women and men, which primarily reflect unique joint behavior in the very elderly. Second, gait behavior of elderly women is cadence-dependent, consistent with their higher cadence and lower walk ratio. Third, sex-specific differences in walk ratio, the hip maximal angle range, peak extension timing at the hip and knee joints, and the peak timing of flexion angular velocities at the hip and knee joints were unusual for elderly individuals. The findings of this dissertation would be useful as to identify and monitor the parameters that are reflective of gait characteristics in the elderly population.

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