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Kinematic and Kinetic Analysis of Gait in Maintenance Hemodialysis Patients

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Abstract To elucidate the gait characteristics of hemodialysis patients, their gaits were analyzed from kinematic and kinetic viewpoints. The gait of 23 patients in the hemodialysis group was measured using a motion capture system and a force plate. We calculated the joint angles and joint moments of the hip, knee, and ankle joints during one gait cycle. The hemodialysis group was compared with 30 patients in a control group utilizing the AIST gait database 2019. The hemodialysis group had a shorter step length and a greater step width than the control group. In the hemodialysis group, the hip flexion angle at the initial contact, the knee flexion angle at the loading response, and the hip flexion angle at the terminal swing were small. The ankle plantarflexion angle at the loading response and the knee flexion angle at the terminal stance were large. The hip extension moment in the loading response and the knee extension moment in the pre-swing were also large. The knee extension moment and the ankle joint dorsiflexion moment in the loading response were small, as was the knee joint flexion moment at the terminal stance. The walking velocity of the hemodialysis patients was maintained by increasing the walking rate against the reduced step length to increase walking stability in the front–back direction. However, the step width was increased to increase stability in the lateral direction, resulting in inefficient walking. The heel rocker was not functioning in the loading response, so the hip extension moment was increased to provide stable weight-bearing and forward body movement. From the terminal stance to the pre-swing, the knee joint extension increased to control the knee joint and compensate for forward acceleration. The gait of maintenance hemodialysis patients was different from that of healthy subjects. Compensatory movements were observed to compensate for the difference, resulting in inefficient gait. If compensatory movements are observed and walking becomes inefficient, it is predicted to decrease independence in walking, cause a decline in ADL, and fall in the future. Therefore, it is necessary to improve the function of the lower limb joints, especially the knee and ankle joints, reduce the burden on other muscles and joints, and modify the gait to use the muscles that should be used.

Keywords Hemodialysis, Gait Characteristics, Kinematic, Kinetic

1. Introduction

Hemodialysis patients in Japan have a better prognosis and lower mortality about one year after induction of dialysis compared with other countries [1]. Of course prolonged duration of hemodialysis parallels patient aging. In addition, the age at which patients start hemodialysis is increasing. Thus aging has become a problem for hemodialysis patients in Japan [2]. Therefore, the therapeutic goal is to improve life prognosis and focus on enhancing Activities of Daily Living (ADL) and Quality of Life (QOL).

Hemodialysis is not able to completely replace renal function. Prolonged hemodialysis is often associated with diverse and specific complications, such as dialysis amyloidosis, infection, atherosclerosis, and nutritional disorders. Complications leading to locomotor disorders are likely to lead to deterioration of ADL and QOL. Musculoskeletal disorders such as osteoarthritis and pain are present in 76.4% of dialysis patients and are related to the duration of dialysis and age [3]. Dialysis amyloidosis is one of the most common complications of hemodialysis, leading to locomotor disorders. Amyloid fibrils tend to be deposited in the osteoarticular region, causing locomotor disability. Dialysis amyloidosis is associated with increasing duration of hemodialysis and patient age. It is often associated with systemic symptoms such as dialysis spondylolisthesis (destructive spondyloarthropathy and spinal canal stenosis), carpal tunnel syndrome, bone cysts, and trigger finger, all of which impact ADL and impair QOL [4,5]. Another complication that leads to locomotor disorders is secondary hyperparathyroidism, a major complication in hemodialysis patients, causing heterotopic ossification and bone pain and deformity associated with fibrous osteitis, resulting in motor impairment and affecting ADL [6].

Hemodialysis patients also experience additional age-related problems. Seventy-seven percent of hemodialysis patients suffer geriatric impairments in their ADL, instrumental ADL, and cognitive functions [7]. The physiological aging of the body progresses with age, and the elderly show physical characteristics such as dulled sense of touch, decreased bone density, decreased muscle mass, decreased muscle strength, decreased joint range of motion, osteoarthritis, and decreased walking ability. In the elderly, age-related functional decline and loss of reserve strength, combined with factors such as decreased physical activity, poor nutrition, and sarcopenia, can lead to frailty. Hemodialysis patients have a decreased exercise capacity [8]. In addition, hemodialysis patients have a higher incidence of frailty [9–11], higher annual fall rate [12–14], and increased proximal femur fracture rate [15].

Walking is an important component of ADL and a diagnostic criterion for frailty. Walking in hemodialysis patients is an important indicator associated with mortality, hospitalization, and changes in functional status [11,16]. In addition, walking velocity is closely related to ADL, instrumental ADL, falls, and risk of mortality, leading to a decline in future life functions [17–19]. Therefore, maintenance and improvement of walking in hemodialysis patients are likely to improve ADL and QOL. However, only walking velocity has been analyzed as a performance indicator for hemodialysis patients, kinematic and kinetic analyses have not been reported, and consequently no intervention strategies for walking movements have been clarified [20]. The purpose of this study is to analyze the gait of hemodialysis patients from a kinematic and kinetic point of view, clarify their gait characteristics, and examine the physical therapy that leads to the prevention of decreased independence in gait, decreased ADL, and falls.

2. Methods

2.1. Participants

The hemodialysis group comprised 23 patients (16 males and seven females, mean age 71.5 ± 6.8 years) who had been on outpatient hemodialysis for more than one year and were over 60 years old and could walk independently without assistance such as a cane on a daily basis. Exclusion criteria were as follows: those with pacemakers or other medical electronic devices that made it difficult to undergo bioimpedance testing, those with a history of cerebrovascular disease, those undergoing trauma treatments, and those with a score of 21 or less on the Mini-Mental State Examination (MMSE). As the control group, we utilized the Advanced Industrial Science and Technology (AIST) gait database 2019 [21]. From the gait data of the 300 healthy adults in the database, we selected 30 individuals matched with the hemodialysis group in terms of age, sex, height, and weight composition.

2.2. AIST Gait Database 2019

The AIST Gait Database 2019 is a database of gait data measured by the National Institute of Advanced Industrial Science and Technology (AIST) using a motion capture system (Vicon MX system and Vicon Nexus from Vicon, Oxford, UK) and force plates (BP400600-1000 and BP400600-2000 from AMTI, Watertown, MA, USA). The sampling frequency was 200 Hz for the motion capture system and 1,000 Hz for the force plate. To perform measurements, the subject was asked to don the measurement suit and stand in the reference posture (upright posture) so that the positions of the markers could be recorded. This was followed by barefoot gait measurement, when the subjects were instructed to "walk straight at a comfortable pace as you usually walk in your daily life" along a 10 meter path, and after several practice trials, a total of 10 trials–five each on the left and right sides–were measured. Low-pass Butterworth filtering at 6 Hz was applied to the marker and landing point positions, and 10 Hz low-pass Butterworth filtering was applied to the force plate data to remove high-frequency noise.

2.3. Measurement

The following items were evaluated and measured in the hemodialysis group: basic information, clinical severity classification of amyloidosis on hemodialysis, Japanese Orthopedic Association joint function assessment (JOA score), revised Japanese Cardiovascular Health Study criteria (J-CHS), and gait analysis.

2.3.1. Basic information

Basic information extracted from medical records consisted of age, sex, height, weight, primary hemodialysis disease, hemodialysis duration, and complications. Body mass index (BMI) was calculated from height and weight.

2.3.2. Dialysis amyloidosis clinical severity classification

The dialysis amyloidosis clinical severity classification was developed as an index to evaluate the clinical severity of dialysis amyloidosis by weighting the presence or absence of major symptoms that strongly affect physical function [4]. Polyarthralgia, trigger finger, carpal tunnel syndrome, and dialysis-related spondyloarthropathy were all rated as present (1) or absent (0). Each was multiplied by a coefficient to calculate the total amyloid stage index. Based on the calculated amyloid stage index, the severity of the disease was determined as follows: four points or less was classed as mild, five to seven points as moderate, and eight or more points as severe.

2.3.3. JOA score

The JOA score is a chart established by the Japanese Orthopedic Association for evaluating shoulder, knee, and hip joint diseases. It is used as a standard for judging orthopedic physical function. It can be used to objectively evaluate physical functions by quantifying them (on a 100-point scale). In this study, we used the evaluation charts for the hip joint (hip JOA score) [22], knee joint (knee JOA score) [23], and foot (foot JOA score) [24]. The hip JOA score consisted of pain (40 points), range of motion (20 points), walking ability (20 points), and ADL (20 points). The JOA score for the knee joint consisted of pain and ability to walk (30 points), pain and ability to climb stairs (25 points), flexion angle and tenseness/high contracture (35 points) and swelling (10 points). The foot JOA score consisted of pain (20 points), deformity (30 points), range of motion (10 points), instability (10 points), walking ability (10 points), muscle strength (5 points), sensory abnormalities (5 points), and ADL (10 points). Both left and right joints were evaluated, and the average value was recorded.

2.3.4. J-CHS

The J-CHS was developed as an index suitable for elderly Japanese people based on the CHS criteria, which are commonly used internationally to assess frailty [25]. The evaluation items are weight loss (unintentional weight loss of 2 kg or more in 6 months), muscle weakness (grip strength: men < 28 kg, women < 18 kg), fatigue (feeling tired for no reason for the last 2 weeks), decreased walking velocity (normal walking velocity < 1.0 m/sec), decreased activity (light exercise/calisthenics, regular exercise/sports: none of the two is done more than once a week). If three or more of these five signs apply, the patient is classified as frail; if one or two apply, the patient is pre-frail; and if none apply, the patient is robust (healthy). Grip strength was measured using a grip strength meter (Tsutsumi Seisakusho Co., Ltd.: TTM Smedley grip strength meter 100 kg YoII) twice on each side, and the best value was recorded. The 10-meter normal walking speed was measured with a stopwatch over a 10-meter stretch of the 14-meter walk. Measurements were made twice, and the average value was recorded.

2.3.5. Gait analysis

For gait analysis, one force plate (AccuGait, AMTI) and eight digital 4K cameras (Hero8, GoPro, San Mateo, CA, USA) were used for measurement. The digital 4K cameras were set up around the 4-meter walking path where the force plate was installed, and the walking motion was filmed from the front, back, left, right, and diagonal directions. The sampling frequency was set to 60 Hz, and an optical synchronization signal generator (PH-145, KKDK) was used for synchronization. The walking velocity was set to the usual walking speed of each subject. The number of measurements was set to three for each side for each subject. Markers (15 mm in diameter) were attached to the acromion, greater trochanter, lateral knee joint space, external capsule, and fifth metatarsal head on both sides. The captured images were imported into a three-dimensional motion analysis system (Frame-DIAS 6; DKH Corporation, Tokyo, Japan), and the three-dimensional spatial coordinates of the markers were calculated. The three-dimensional spatial coordinates and the data obtained from the force plate were converted into DIFF (Date Interface File Format) format and then converted into Excel format using DIFF gait and Wave Eyes, software provided by the Clinical Gait Analysis Study Group [26]. The joint angles and joint moments of the hip, knee, and ankle joints during one gait cycle were calculated from the data in Excel format.

2.4. Statistical Analysis

The $\chi 2$ test was used to compare the proportion of males and females between the two groups. Age, height, weight, BMI, joint angles and moments during one walking cycle, and gait parameters (step length, step width) between the two groups were tested for normality (Shapiro-Wilk test). We then performed an unpaired t-test if the distribution followed a normal distribution and a Mann-Whitney test if it did not follow a normal distribution. For comparison of JOA scores in the hemodialysis group, one-way analysis of variance was used to confirm significance and the Tukey method was used for multiple comparisons. The statistical software SPSS version 19 (IBM SPSS Statistics for Windows, Armonk, NY, USA) was used for analysis. Values are expressed as mean ± standard deviation, and the significance level was set at 5%.

3. Results

3.1. Patient Information for Hemodialysis Group (Table 1, 2)

Table 1. Characteristics of the hemodialysis group

Characteristic	Value
Patient (n)	23
Age (year)	71.5 ± 6.8
Sex (n (%))	
Male	16 (69.6)
Female	7 (30.4)
Hemodialysis-induced illness (n (%))	
Chronic glomerulonephritis	9 (39.1)
Diabetic nephropathy	8 (34.8)
Other	6 (26.1)
Dialysis duration (year (min-max))	16.7 ± 12.0 (1-46)
Dialysis-related amyloidosis (n (%))	9 (39.1)
Dialysis-related amyloidosis symptoms (n (%))	
Polyarthralgia	11 (47.8)
Carpal tunnel syndrome	8 (34.8)
Trigger finger	6 (26.1)
Dialysis-related spondyloarthropathy	5 (21.7)
Amyloid Clinical Stage (n (%))	
Light	14 (65.2)
Moderate	4 (17.4)
Severe	4 (17.4)
Secondary hyperparathyroidism (n (%))	21 (91.3)
J-CHS score (n (%))	
Frail	5 (21.7)
Pre-frail	12 (52.2)
Robust	6 (26.1)

The hemodialysis group consisted of 23 patients with 23 limbs measured without pain and disability. The primary hemodialysis diseases were chronic glomerulonephritis (nine patients), diabetic nephropathy (eight patients), and others (six patients), and the duration of hemodialysis was 16.7 ± 12.0 years (1–46 years). Regarding complications related to hemodialysis, dialysis amyloidosis was diagnosed in nine patients. Eleven patients had polyarticular pain, five patients had carpal tunnel syndrome, six patients had trigger finger, and five patients had dialysis-related spondyloarthropathy as symptoms of dialysis amyloidosis. The clinical severity classification of dialysis amyloidosis was mild (≤ 4 points) in 15 patients, moderate (5 − 7 points) in four patients, and severe (8–10 points) in four patients. The JOA scores were 91.2 ± 10.0 for hip, 86.7 ± 13.5 for knee, and 86.0 ± 11.1 for foot, and the comparisons among the three groups showed that the JOA scores for hip and knee (p = 0.409), hip and foot (p = 0.295), and knee and foot (p = 0.973) were not significantly different. The J-CHS classification was frail in five patients (21.7%), pre-frail in 12 patients (52.2%), and robust in six patients (26.1%).

Table 2. JOA score of the hemodialysis group

JOA score	Value
Hip joint (point (perfect score))	91.2 ± 10.0 (100) *
Pain	39.1 ± 2.8 (40)
Range of motion	19.2 ± 1.7 (20)
Walking ability	15.3 ± 4.8 (20)
Activities of daily living	17.6 ± 3.0 (20)
Knee joint (point (perfect score))	86.7 ± 13.5 (100) *
Pain / walking ability	25.9 ± 6.7 (30)
Pain / stair climbing ability	22.4 ± 3.4 (30)
Flexion angle and ankylosis/high contracture	28.5 ± 7.3 (30)
Swelling	10.0 ± 0.0 (10)
Ankle joint (point (perfect score))	86.0 ± 11.1 (100) *
Pain	19.9 ± 0.5 (20)
Deformation	28.0 ± 4.3 (30)
Range of motion	8.0 ± 2.2 (10)
Instability	9.7 ± 1.3 (10)
Walking ability	6.8 ± 2.3 (10)
Strength	3.2 ± 1.6 (5)
Paresthesia	3.9 ± 1.6 (5)
Activities of daily living	6.4 ± 2.5 (10)

*For comparison of JOA scores of each joint, one-way analysis of variance was used to confirm significance, and the Tukey method was used for multiple comparisons. No significant differences were found.

3.2. Comparison of Attributes and Gait Parameters between Hemodialysis Group and Control Group (Table 3)

The hemodialysis group consisted of 23 patients (16 males and seven females) with a mean age of 71.5 ± 6.8 years. The control group consisted of 30 patients (21 males and nine females) with a mean age of 71.5 ± 3.9 years. There were no significant differences in the sex ratio, age, height, weight, or body mass index between the two groups.

The walking velocity and walking rate in the hemodialysis group were 1.14 ± 0.18 m/sec and 119.9 ± 10.1 steps/min. The walking speed and walking rate of the control group could not be compared because the data were not available in the AIST gait database 2019. The step length was 0.30 ± 0.07 m/m in the hemodialysis group compared to 0.39 ± 0.03 m/m in the control group ($p < 0.001$). Step width was 0.09 ± 0.03 m/m in the hemodialysis group compared to 0.06 ± 0.02 m/m in the control group ($p < 0.001$).

Table 3. Comparison of characteristics and gait parameters of participants between the hemodialysis group and the control group

	Hemodialysis group n=23	Control group n=30	p-value
Age (year)	71.5±6.8	71.5±3.9	0.822
Height (m)	1.64±9.15	1.60±6.70	0.074
Weight (kg)	59.4±11.2	57.8±6.2	0.533
Body mass index (kg/m²)	22.1±3.1	22.7±2.3	0.404
Sex (n (%))			
Male	16 (69.6)	21 (70.0)	0.973
Female	7 (30.4)	9 (30.0)	
Walking velocity (m/sec)	1.14±0.18	*	*
Walking rate (steps/min)	119.9±10.1	*	*
Step length Step length/height (m/m)	0.30±0.07	0.39±0.03	<0.001
Step width Step width/height (m/m)	0.09±0.03	0.06±0.02	<0.001

*The walking velocity and walking rate of the control group could not be compared with that of the dialysis group because the data were not available in the AIST walking database 2019.

3.2. Comparison of Each Joint Angle during One Walking Cycle between the Hemodialysis Group and the Control Group (Table 4, Fig. 1)

The hip flexion angle at initial contact was 21.1 ± 5.6° in the hemodialysis group compared to 33.8 ± 5.9° in the control group ($p < 0.001$). There was no significant difference in the knee joint flexion angle. In the loading response, the knee joint flexion angle was 16.2 ± 9.5° in the hemodialysis group compared to 21.5 ± 3.9° in the control group ($p = 0.018$), and the ankle plantarflexion angle was 6.9 ± 4.9° in the hemodialysis group compared to 2.9 ± 2.1° in the control group ($p = 0.004$). At the terminal stance, the knee joint flexion angle was 9.9 ± 8.1° in the hemodialysis group compared to 4.5 ± 4.9° in the control group ($p = 0.008$), but no significant differences were observed in hip extension or ankle dorsiflexion angles. At the terminal swing, the hip flexion angle was 23.2 ± 5.6° in the hemodialysis group compared to 35.5 ± 6.6° in the control group ($p < 0.001$), but there was no significant difference in the knee joint flexion angle. There was no significant difference in ankle plantarflexion angle in the pre-swing or in knee joint flexion angle in the initial swing.

3.3. Comparison of Each Joint Moment during One Walking Cycle between the Hemodialysis Group and the Control Group (Table 4, Fig. 2)

In the loading response, the hip extension moment was 0.80 ± 0.26 Nm/kg in the hemodialysis group compared to 0.52 ± 0.16 Nm/kg in the control group ($p < 0.001$); the knee extension moment was 0.17 ± 0.33 Nm/kg in the hemodialysis group compared to 0.54 ± 0.15 Nm/kg in the control group ($p < 0.001$), and the dorsiflexion moment of the ankle joint was 0.01 ± 0.06 Nm/kg in the hemodialysis group compared to 0.15 ± 0.06 Nm/kg in the control group ($p < 0.001$). At the terminal stance, the knee joint bending moment was 0.03 ± 0.32 Nm/kg in the hemodialysis group compared to 0.23 ± 0.13 Nm/kg in the control group ($p = 0.018$), but there was no significant difference in the hip flexion moment or the ankle plantarflexion moment. In the pre-swing, the knee extension moment was 0.35 ± 0.18 Nm/kg in the hemodialysis group compared to 0.17 ± 0.08 Nm/kg in the control group ($p < 0.001$). There was no significant difference in the knee joint flexion moment at initial contact between the two groups.

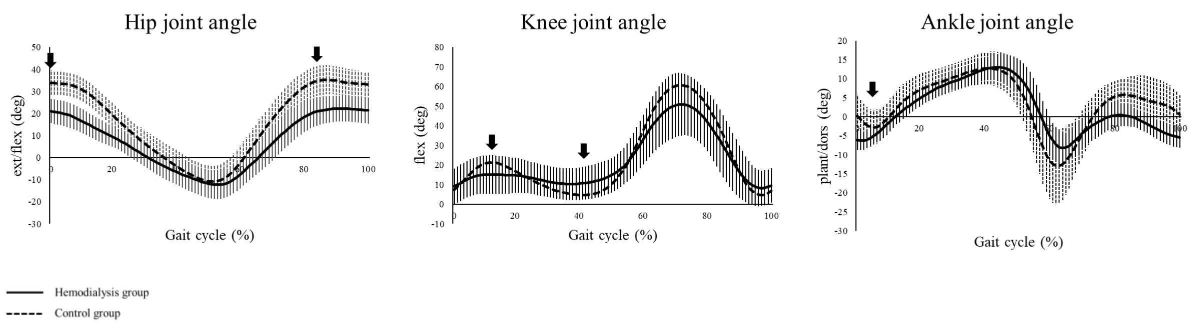

Figure 1. The joint angles in the hemodialysis group and the control group during one gait cycle.

Mean and SD of joint angles during one gait cycle.
The values of the hemodialysis group are presented as a solid line, and for the control group as a dotted line.
The positions where significant differences were observed between the hemodialysis group and the control group are indicated by arrows (➡).

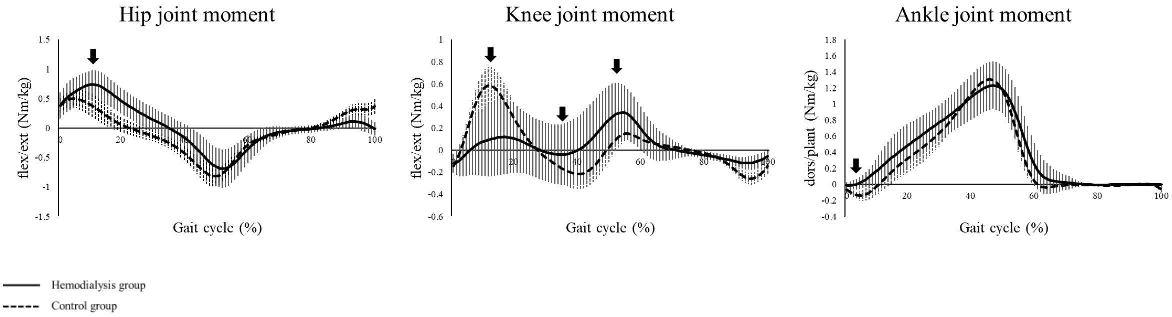

Figure 2. The joint moments in the hemodialysis group and the control group during one gait cycle.

Mean and SD of joint moments during one gait cycle.

The values of the hemodialysis group are presented as a solid line, and for the control group as a dotted line.

The positions where significant differences were observed between the hemodialysis group and the control group are indicated by arrows (➡).

Table 4. Comparison of joint angles and joint moments between the hemodialysis group and the control group

	Hemodialysis group n = 23	**Control group n = 30**	***p*-value**
Joint angle (deg)			
Hip joint			
Flexion [Initial contact]	21.1 ± 5.6	33.8 ± 5.9	<0.001
Extension [Terminal stance]	13.5 ± 6.4	11.0 ± 7.4	0.212
Flexion [Terminal swing]	23.2 ± 5.6	35.5 ± 6.6	<0.001
Knee joint			
Flexion [Initial contact]	9.2 ± 9.2	7.4 ± 2.9	0.368
Flexion [Loading response]	16.2 ± 9.5	21.5 ± 3.9	0.018
Flexion [Terminal stance]	9.9 ± 8.1	4.5 ± 4.9	0.008
Flexion [Initial swing]	55.3 ± 12.7	61.1 ± 4.2	0.085
Flexion [Terminal swing]	8.3 ± 7.6	4.3 ± 3.5	0.167
Ankle joint			
Plantarflexion [Loading response]	6.9 ± 4.9	2.9 ± 2.1	0.004
Dorsiflexion [Terminal stance]	14.1 ± 4.9	13.1 ± 2.8	0.386
Plantarflexion [Pre-swing]	11.4 ± 5.9	13.6 ± 4.3	0.140
Joint moment (Nm/kg)			
Hip joint			
Extension [Loading response]	0.80 ± 0.26	0.52 ± 0.16	<0.001
Flexion [Terminal stance]	0.74 ± 0.32	0.83 ± 0.18	0.282
Knee joint			
Flexion [Initial contact]	0.13 ± 0.09	0.15 ± 0.06	0.355
Extension [Loading response]	0.17 ± 0.33	0.54 ± 0.15	<0.001
Flexion [Terminal stance]	0.03 ± 0.32	0.23 ± 0.13	0.018
Extension [Pre-swing]	0.35 ± 0.18	0.17 ± 0.08	<0.001
Ankle joint			
Dorsiflexion [Loading response]	0.01 ± 0.06	0.15 ± 0.06	<0.001
Plantarflexion [Terminal stance]	1.30 ± 0.26	1.32 ± 0.13	0.844

4. Discussion

4.1. Patient Information in the Hemodialysis Group

The prevalence of frailty in the hemodialysis group was low, but most of the patients were in a frail state. The prevalence of frailty in hemodialysis patients aged 70–80 years has been reported to be 78.1% [10], while in the hemodialysis group in this study, the prevalence of frailty according to the J-CHS classification was only 21.7%. Thus the prevalence of frailty was much lower in the hemodialysis group than in previous studies. However, the dialysis group was older (the mean age of the patients was 71.5 years), and 73.9% of them were near frail if the classification of pre-frail was included. Walking in the hemodialysis group was possibly affected by diabetic complications. Chronic glomerulonephritis was the most common primary hemodialysis disease, followed by diabetic nephropathy (34.8%). The major complications of diabetes are visual impairment due to diabetic retinopathy and pain and sensory impairment due to diabetic neuropathy. The possibility that diabetic complications affect walking velocity and stability of gait should be considered. The incidence of dialysis amyloidosis was slightly lower in the hemodialysis group. The first symptom of dialysis amyloidosis is carpal tunnel syndrome, and the time of onset after starting hemodialysis has been reported to be 86.1 ± 36.3 months. [27]. However, it has been reported that up to 50% of hemodialysis patients develop carpal tunnel syndrome after 20 years, and the rate is even higher after 25 years [28]. In the hemodialysis group, carpal tunnel syndrome was observed in 34.8% of patients and other signs of dialysis amyloidosis were also observed. The hemodialysis group had been on hemodialysis for a shorter period (16.7 years), which may have resulted in the lower incidence of dialysis amyloidosis. The proportion of patients with secondary hyperparathyroidism was 91.3%, and polyarticular pain was observed in 47.8% of the patients. The prevalence of secondary hyperparathyroidism was reported to be 81%, with symptoms including bone pain and stiffness, joint pain, muscular pain, generalized pain, itchy skin, and worsening malaise [6]. The prevalence was slightly higher in the hemodialysis group. Thus, the hemodialysis group in this study were in a frail state due to aging, diabetic complications, dialysis amyloidosis, and secondary hyperparathyroidism. Musculoskeletal symptoms were present in 76.4% of hemodialysis patients, with pain being the most frequent symptom, followed by musculoskeletal symptoms, and disability related to the duration of hemodialysis and age [3]. In the present study, although the JOA score did not differ significantly between the joints, it inferred that these complications interacted to cause a decline in motor function.

4.2. Gait Parameters

The walking velocity of the hemodialysis group was 1.14 ± 0.18 m/sec, and the walking rate was 119.9 ± 10.1 steps/min. Previous studies of the walking parameters of hemodialysis patients reported that the walking velocity was 1.01 m/s [29], and the walking rate was 100.1 ± 12.6 steps/min [30]. In our hemodialysis group, the walking velocity was relatively maintained, and the walking rate was higher. However, in comparing the hemodialysis group and the control group, the hemodialysis group had a shorter step length and a wider step width. One of the characteristics of age-related changes in gait is a decrease in walking velocity, which is related to a decrease in both step length and walking rate. The hemodialysis group may maintain walking velocity by increasing the walking rate to compensate for the shortened step length. In addition, the decrease induces an increase in step width to improve support and balance functions, including muscle strength, which widens the base of support during walking and increases stability in the lateral direction. However, the stability in the front–back direction was compensated by shortening the step length, but the walking velocity did not decrease significantly, suggesting that the walking was inefficient.

4.3. The Difference in Each Joint Angle during One Walking Cycle between the Hemodialysis Group and the Control Group

In the initial contact, the knee joint flexion angle was greater than normal gait in both groups, although the difference was not significant. However, the hip flexion angle of the hemodialysis group was close to the standard value, while that of the control group was larger than the standard value. In both groups, the knee flexion angle at initial contact was large. In the control group, the step length was compensated for by increasing the hip flexion angle, but in the hemodialysis group, the hip flexion angle remained within the normal range, resulting in a smaller step length. The hip JOA score in the hemodialysis group did not suggest a significant decrease in hip function. Therefore, it is thought that the hip joint flexion angle at initial contact did not limit the hip joint's decreased mobility but that the step length reduced to improve walking stability in the front–back direction.

In the loading response, the control group increased the knee joint flexion angle from the initial contact to the loading response, which resulted in stable weight-bearing and forward body movement. In contrast, the hemodialysis group entered the loading response with no significant change from the knee joint flexion angle at the initial contact. The knee joint JOA score of the hemodialysis group did not show a significant decrease in knee joint function, suggesting that the knee joint immobilized during gait and inhibited standard motion. In the control group, the ankle joint was initially grounded at

0 degrees, and then the heel rocker functioned as the ankle joint bottom flexed toward the loading response. However, in the hemodialysis group, the ankle joint was initially grounded at the bottom flexion position, with initial contact occurring in the plantarflexion position of the ankle joint, suggesting that the adjustment of the load transfer at the knee joint and ankle joint did not function well, and the forward movement of the body was not smooth.

At the terminal stance, the hemodialysis group showed less knee joint flexion during the loading response and less knee joint extension. Those may have reduced the forward acceleration.

At the terminal swing, the hip flexion angle related to the initial contact, so there was a difference in the hip flexion angle as in the initial contact.

4.4. Differences in Joint Moments during One Walking Cycle between the Hemodialysis Group and the Control Group

The hip extension moment was greater in the hemodialysis group than in the control group during the loading response, while the knee extension moment and ankle dorsiflexion moment were smaller. The knee joint flexes to buffer the load during the loading response, resulting in the greatest knee joint extension moment. However, in the hemodialysis group, the knee joint flexion angle did not change significantly from the initial contact to the terminal stance, so the knee joint extension moment did not increase, and the hip joint extension moment increased to support the body weight and move the body forward while stabilizing the pelvis and thighs.

At the terminal stance, the knee joint flexion moment of the hemodialysis group was lower than that of the control group. At the terminal stance, the knee joint flexion moment of the hemodialysis group was smaller than that of the control group, and the knee joint extension moment of the hemodialysis group was larger than that of the control group. In the terminal stance, the knee joint flexion moment controls knee joint hyperextension, and in the pre-swing, the knee joint extension moment controls knee joint flexion. However, in the hemodialysis group, the knee joint flexion angle did not change significantly from the initial contact to the terminal stance, suggesting that the knee joint extension moment compensated for knee joint control and forward acceleration.

5. Conclusions

This study compared and analyzed the gait of hemodialysis patients and healthy subjects from the kinematic and kinetic viewpoints to clarify the gait characteristics of hemodialysis patients. Hemodialysis patients grounded their gait with a large knee joint flexion angle. They did not compensate for their step length by increasing the hip joint flexion angle but reduced their step length to improve their walking stability in the front–back direction. In response to the reduced step length, the walking velocity was maintained by increasing the walking rate. To increase the stability in the lateral direction, the step width increased, but the walking velocity did not significantly decrease, resulting in inefficient walking. During the loading response, the knee joint was fixed, and the heel rocker was not functioning, so the knee joint extension moment and ankle joint dorsiflexion moment were inadequate, and by increasing the hip joint extension moment, stable weight-bearing and forward body movement were performed. In addition, from the terminal stance to the pre-swing, knee joint extension was not observed, and consequently forward acceleration was reduced.

Thus, the gait of maintenance hemodialysis patients was different from that of healthy subjects. Compensatory movements were observed to compensate for the difference, and it became clear that the gait was inefficient. In compensatory movements, joint movements and muscles that should be used are not used. The muscles and joints that are not used become less functional. In addition, compensatory movements can lead to pain due to the overload of muscles and joints that have been used excessively. If the compensatory movement continues for a long time, it may cause osteoarthritis due to the strain on the joints. When compensatory movements are observed and walking becomes inefficient, it is predicted to decrease independence in walking, cause a decline in ADL, and fall in the future. Therefore, it is necessary to improve the function of the lower limb joints, especially the knee and ankle joints, reduce the burden on other muscles and joints, and modify the gait to use the muscles that should be used.

Conflict of Interest

We declare that there are no competing interests associated with the research reported within this manuscript. No source of funding was used in the undertaking of this study or the preparation of this manuscript.

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