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Gait Classification and Physical Function Characteristics in Maintenance Hemodialysis Patients

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Abstract Only walking velocity has been reported as a performance measure of gait in hemodialysis patients, and no kinematic or kinetic analysis has been reported. We evaluated basic information, physical function, aging, dialysis-related complications, and gait in 23 outpatients (≥60 years old) who could walk independently. Hierarchical cluster analysis was performed using joint angles, joint moments, and gait parameters during gait. The gait of hemodialysis patients was classified into two clusters: Cluster 1 and Cluster 2. Cluster 1 gait showed a longer hemodialysis duration, higher dialysis amyloidosis severity, knee joint pain, lower ankle plantarflexion weakness, and lower extremity joint dysfunction than Cluster 2. The gait of Cluster 1 patients consisted of flexion of the knee joint, ankle joint, and trunk, and excessive knee joint flexion was observed in the stance phase to escape posterior knee joint pain. Cluster 1 patients were also unable to kick out sufficiently, and their walking rate and walking velocity were decreased. Cluster 2 patients had a shorter hemodialysis duration than Cluster 1. External forces exerted on the knee joint in the hyperextension direction during gait could cause pain and inflammation of the posterior knee joint.

Keywords Hemodialysis, Kinematic, Kinetic, Gait Characteristics

1. Introduction

The mortality of maintenance hemodialysis patients is much higher than that of the general population, and mortality varies widely from country to country [1]. In addition, physical function, activities of daily living (ADL), quality of life (QOL), and physical activity contribute to survival and mortality in maintenance hemodialysis patients [2]. Therefore, treatment goals for maintenance hemodialysis patients focus on improving ADL, QOL, and life expectancy.

Prolonged hemodialysis therapy can be associated with diverse and specific complications such as dialysis amyloidosis, infections, atherosclerosis, and nutritional disorders. Complications that lead to motor impairment may lead to a decrease in ADL and QOL [3]. Blood β2-microglobulin, a precursor protein of dialysis amyloidosis, is deposited preferentially at osteoarticular sites and tends to cause musculoskeletal disorders [4]. The duration of hemodialysis and aging triggers dialysis amyloidosis. Dialysis spondylolisthesis (destructive spondyloarthropathy and scoliosis), carpal tunnel syndrome, bone cysts, spring toe, and other systemic symptoms often impair ADL and QOL [5]–[7].

Walking is an important component of ADL and a diagnostic criterion for frailty. In hemodialysis patients, walking is an important indicator associated with mortality, hospitalization, and changes in functional status [8], [9]. In addition, walking velocity is closely related to ADL, instrumental ADL, falls, and risk of death, leading to a decline in future life functions [10]–[12]. Therefore, maintaining or improving gait in hemodialysis patients will likely improve ADL and QOL. However, walking in hemodialysis patients has been analyzed only in terms of walking velocity as a performance index, while kinematic and kinetic analyses have not been reported. Thus, intervention strategies for walking in hemodialysis patients are not clear [13].

In the present study, we identified subgroups of hemodialysis patients based on kinematic and kinetic gait data to confirm their gait characteristics. We aimed to clarify the gait characteristics of hemodialysis patients and examine intervention methods that can lead to continued independence in walking, decreased ADL, and prevention of falls.

2. Materials and Methods

Subjects were 23 patients (16 males and 7 females; mean age, 71.5±6.8 years) who had been on outpatient hemodialysis for at least one year, were at least 60 years old, and could walk independently without assistance, such as a cane. Exclusion criteria were those who were unable to undergo bioimpedance testing due to a pacemaker or other medical electronic device, those with a history of cerebrovascular disease, those undergoing trauma treatment, and those with a Mini-Mental State Examination (MMSE) score of 21 or less. This study was approved and conducted by the Ethics committee of Syutaikai Medical Corporation (Approval No. 2019-13).

2.1. Basic Information

Demographic and clinical information was collected from medical records, including age, sex, height, weight, primary hemodialysis disease, hemodialysis duration, and complications.

2.2. Physical Function

Lower limb muscle strength was measured using a muscle tester (μTas F-1, Anima Co. Ltd., Tokyo, Japan) to measure isometric hip flexor strength, isometric hip extensor strength, isometric knee extensor strength, and isometric ankle plantar flexor strength, which are the major muscle forces that affect walking. Each muscle force was subjected to a maximal isometric contraction for approximately 3 seconds. Measurements were taken twice on each side with an interval of at least 30 seconds, and the maximum value was used for each side. Muscle strength value (kgf/kg) was calculated by dividing the average value (kgf) of the two sides by the body weight (kg).

The JOA score is used to assess orthopedic physical function and was established by the Japanese Orthopaedic Association. In this study, we used evaluation charts for the hip joint (hip JOA score) [14], knee joint (knee JOA score) [15], and foot (foot JOA score) [16]. The hip JOA score consists of pain (40 points), range of motion (20 points), ability to walk (20 points), and ADL (20 points). The knee joint JOA score consists of pain and ability to walk (30 points), pain and ability to climb stairs (25 points), flexion angle and ankylosis/severe contracture (35 points), and swelling (10 points). The foot JOA score consists of pain (20 points), deformity (30 points), range of motion in the other foot (10 points), instability (10 points), walking ability (10 points), muscle strength (5 points), sensory abnormalities (5 points), and ADL (10 points). Right and left joints were evaluated, and the average value was used as the record. The scores for each component of the hip, knee, and foot JOA scores were converted to a 100-point scale.

2.3. Frailty and Sarcopenia

The Asian Working Group for Sarcopenia (AWGS) 2019 diagnostic criteria and the Revised J-CHS criteria (J-CHS) were evaluated. The AWGS2019 is a set of criteria for assessing sarcopenia. The three indices are muscle strength, physical function, and skeletal muscle mass. Muscle strength (grip strength) was measured using a 100 kg Smedley grip strength tester (Tsutsumi Corporation, Tokyo, Japan), and the best value was recorded twice on each side. The criteria for low muscle strength was defined as less than 28 kg for males and 18 kg for females. Physical function (10 m normal walking velocity) was measured using a stopwatch to measure the time required between 10 m walking paths out of a 14 m walking path. Measurements were taken twice, and the average value was used as the record. The criterion for determining low physical function was 1.0 m/sec or less for men and women. Skeletal muscle mass was measured by bioelectrical impedance analysis (BIA) using a body composition analyzer (InBody 230; InBody Japan, Inc., Tokyo, Japan), and the value (kg/m^2) was obtained by dividing the muscle mass (kg) of the limbs by the square of their height (m). The low skeletal muscle mass criteria were defined as less than 7.0 kg/m^2 in males and 5.7 kg/m^2 in females. Muscle strength (grip strength), physical function (10 m normal walking velocity), and skeletal muscle mass were defined as sarcopenia if, in addition to a decrease in skeletal muscle mass, there was either a decrease in muscle strength or a decrease in physical function. The presence of all these criteria was defined as severe sarcopenia.

The Revised J-CHS criteria (J-CHS) were developed based on the CHS criteria, commonly used internationally to assess frailty, and adapted to the Japanese elderly [17]. Weight loss (unintentional weight loss of 2 kg or more in six months), muscle weakness (grip strength: men, <28 kg; women, <18 kg), fatigue (feeling tired for no reason in the past two weeks), decreased walking velocity (normal walking velocity, <1.0 m/sec), decreased activity (Respondents reporting neither light exercise/exercise nor regular exercise/sports once a week)

2.4. Dialysis-Related Complications

Nineteen diseases were listed on the Charlson Comorbid

Index (CCI), with higher scores assigned to more severe diseases. A score was assigned to each disease, and the severity of complications was assessed by summing the scores of each disease.

The amyloid clinical stage index (A-stage index) was developed to assess the clinical severity of dialysis amyloidosis by weighting the presence or absence of major symptoms that strongly affect physical function [5]. Arthralgia, spring finger, carpal tunnel syndrome, and dialysis spondylolisthesis were all rated as present (1) or absent (0), each multiplied by a coefficient. The total Amyloid stage index was calculated. From the Amyloid stage index, severity was determined as follows: ≤4 points is considered mild, 5 to 7 points is moderate, and ≥8 points is considered severe.

2.5. Gait Analysis

For gait analysis, a one-floor reaction force unit, Accugait (AMTI, Watertown, MA, USA), and eight Hero8 4K cameras (GoPro, Los Angeles, CA, USA) were used for measurement. Cameras were set around the 4m walking path where the floor reaction force meter was placed, and walking motion was filmed from the front, back, left, right, and diagonal directions. The sampling frequency was 60 Hz, and an optical and synchronous signal generator (PH-145, DKH Corporation, Tokyo, Japan) was used for synchronization. The walking speed was the normal speed of each subject, and measurements were taken three times on each side for each subject. Markers (15 mm in diameter) were placed bilaterally on the acromion, greater trochanter, lateral knee joint crease, external capsule, and fifth metatarsal head. The captured video images were imported into a three-dimensional (3D) motion analysis system (Frame-DIAS 6, DKH Corporation, Tokyo, Japan), and the 3D spatial coordinates of the markers were calculated. The 3D spatial coordinates and data obtained from the floor reaction force meter were converted to DIFF (Date Interface File Format) format and then to Excel format using DIFF gait and Wave Eyes, software provided by the Clinical Gait Analysis Research Group [18]. Angles and moments of the hip, knee, and ankle joints during one gait cycle were calculated from the data in Excel format.

2.6. Statistical Analysis

Hierarchical cluster analysis (Euclidean square distance, Ward's method) was performed using joint angles, joint moments, and gait parameters of the gait of 23 dialysis patients. The optimal number of clusters was determined using gap values [19]. The number of clusters for which the gap values are large was adopted as the optimal value. Gait and physical and motor function characteristics of the classified clusters were compared. The χ^2 test was used to compare proportions between clusters. Comparisons between clusters were subjected to a test of normality (Shapiro-Wilk test) followed by an uncorrelated t-test when following a normal distribution or a Mann-Whitney test when not following a normal distribution. Statistical analyses were performed using the statistical software package R (Ver.4.1.2, R Core Team, 2021) and SPSS version 19 statistical software (SPSS Inc., Chicago, 2011). Values are expressed as mean ± standard deviation, and the significance level was set at 5%.

3. Results

The cluster analysis using joint angles, joint moments, and gait parameters identified two clusters (Figure1). The basic information between the two clusters is shown in Table 1. There were no significant differences between the two clusters in gender, age, body size, skeletal muscle mass, primary hemodialysis disease and hemodialysis duration.

Table 1. Comparison of basic information between two clusters

	Cluster1 (n=12)	Cluster2 (n=11)	p
Sex (n)	9 male/3female	7male/4female	.667
Age (year)	70.1 ± 6.2	73.1 ± 7.4	.298
Height (m)	1.66 ± 0.08	1.61 ± 0.09	.229
Weight (kg)	62.3 ± 9.4	56.4 ± 12.5	.213
Body mass index (kg/m²)	22.7 ± 3.5	21.4 ± 2.7	.358
Skeletal muscle mass index (kg/m²)	6.68 ± 0.86	6.23 ± 1.21	.310
Hemodialysis-induced illness (n)			
Chronic glomerulonephritis	4	5	
Diabetic nephropathy	4	2	.692
Other	4	2	
Hemodialysis vintage (year)	20.8 ± 14.0	12.3 ± 8.6	.138

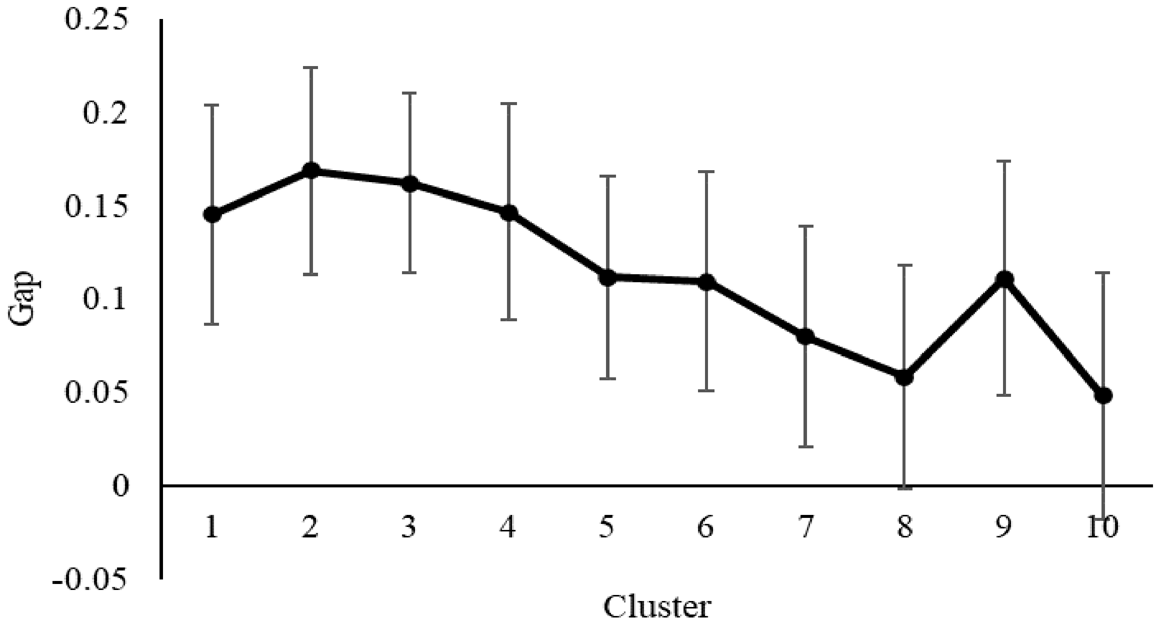

Figure 1. Gap statistics for estimating the number of clusters

3.1. Comparison of Joint Angles and Joint Moments during One Gait Cycle and Gait Parameters between the Two Clusters

Figure 2 and Table 2 show the comparison of results between the two clusters for joint angles and joint moments during gait and gait parameters entered into the cluster analysis.

In terms of joint angles during one gait cycle, the flexion angle of the hip joint at initial ground contact and at the end of the swing phase was significantly greater in Cluster 1 than in Cluster 2 ($p<.001$), and the extension angle of the hip joint at the end of the stance phase was significantly smaller in Cluster 1 than in Cluster 2 ($p<.001$). Cluster 1 had significantly greater flexion angles at the knee joint during initial contact (.001), loading response ($p<.001$), terminal stance ($p<.001$), initial swing ($p=.001$), and terminal swing ($p<.001$) than in Cluster 2. Cluster 1 had significantly greater varus angles of the knee joint in the initial contact ($p<.001$), loading response ($p=.006$), and terminal stance ($p=.017$) than was observed in Cluster 2. The plantarflexion angle of the ankle joint during the loading response was significantly smaller in Cluster 1 than in Cluster 2 ($p<.001$).

In terms of joint moments during one gait cycle, flexion moments of the knee joint were significantly smaller in Cluster 1 compared to Cluster 2 at initial contact ($p<.001$) and at the terminal stance ($p=.001$). Cluster 1 had significantly greater moments of the extension during the loading response and pre-swing of the knee joint compared to Cluster 2 ($p<.001$). Dorsiflexion moments during the loading response of the ankle joint were significantly greater in Cluster 1 than in Cluster 2 ($p=.024$).

Walking velocity for Cluster 1 (1.05±0.19 m/sec) was significantly slower than that for Cluster 2 (1.24±0.13 m/sec) ($p=.031$). The walking rate for Cluster 1 (117.6±7.9 steps/min) was significantly fewer than that for Cluster 2 (122.3±12.3 steps/min) ($p=.010$).

Table 2. Comparison of joint angles and moments between two clusters

	Cluster1 (n=12)	Cluster2 (n=11)	p
Joint angle (deg)			
Hip joint			
Flexion [Initial contact]	25.9 ± 3.4	16.7 ± 4.1	<.001
Extension [Terminal stance]	8.9 ± 3.9	18.5 ± 4.6	<.001
Flexion [Terminal swing]	26.7 ± 3.7	19.5 ± 5.0	<.001
Knee joint			
Flexion [Initial contact]	16.7 ± 4.4	1.1 ± 5.0	<.001
Varus [Initial contact]	6.30 ± 3.67	1.01 ± 2.30	<.001
Flexion [Loading response]	22.6 ± 6.1	9.2 ± 7.3	<.001
Varus [Loading response]	6.61 ± 4.05	2.48 ± 2.09	.006
Flexion [Terminal stance]	16.2 ± 4.9	3.0 ± 4.0	<.001
Varus [Terminal stance]	6.72 ± 4.69	2.04 ± 3.99	.017
Flexion [Initial swing]	61.5 ± 4.4	48.6 ± 15.4	.007
Flexion [Terminal swing]	14.3 ± 5.6	1.7 ± 1.0	<.001
Ankle joint			
Plantarflexion [Loading response]	3.1 ± 2.4	11.0 ± 3.3	<.001
Dorsiflexion [Terminal stance]	15.9 ± 4.8	12.1 ± 4.3	.064
Plantarflexion [Pre-swing]	9.2 ± 4.8	13.9 ± 6.2	.055
Trunk anteversion [one gait cycle]	4.94 ± 5.68	2.08 ± 7.69	.319
Joint moment (Nm/kg)			
Hip joint			
Extension [Loading response]	0.81 ± 0.31	0.78 ± 0.20	.841
Flexion [Terminal stance]	0.75 ± 0.21	0.74 ± 0.41	.538
Knee joint			
Flexion [Initial contact]	0.06 ± 0.04	0.20 ± 0.06	<.001
Extension [Loading response]	0.40 ± 0.26	-0.08 ± 0.17	<.001
Flexion [Terminal stance]	-0.18 ± 0.28	0.27 ± 0.16	.001
Extension [Pre-swing]	0.47 ± 0.16	0.23 ± 0.11	<.001
Ankle joint			
Dorsiflexion [Loading response]	0.04 ± 0.05	-0.01 ± 0.05	.024
Plantarflexion [Terminal stance]	1.29 ± 0.26	1.32 ± 0.27	.124
Walking velocity (m/sec)	1.05 ± 0.19	1.24 ± 0.13	.031
Walking rate (steps/min)	117.6 ± 7.9	122.3 ± 12.3	.010
Step length (m/m)	0.29 ± 0.04	0.31 ± 0.09	.157
Step width (m/m)	0.10 ± 0.03	0.09 ± 0.03	.465

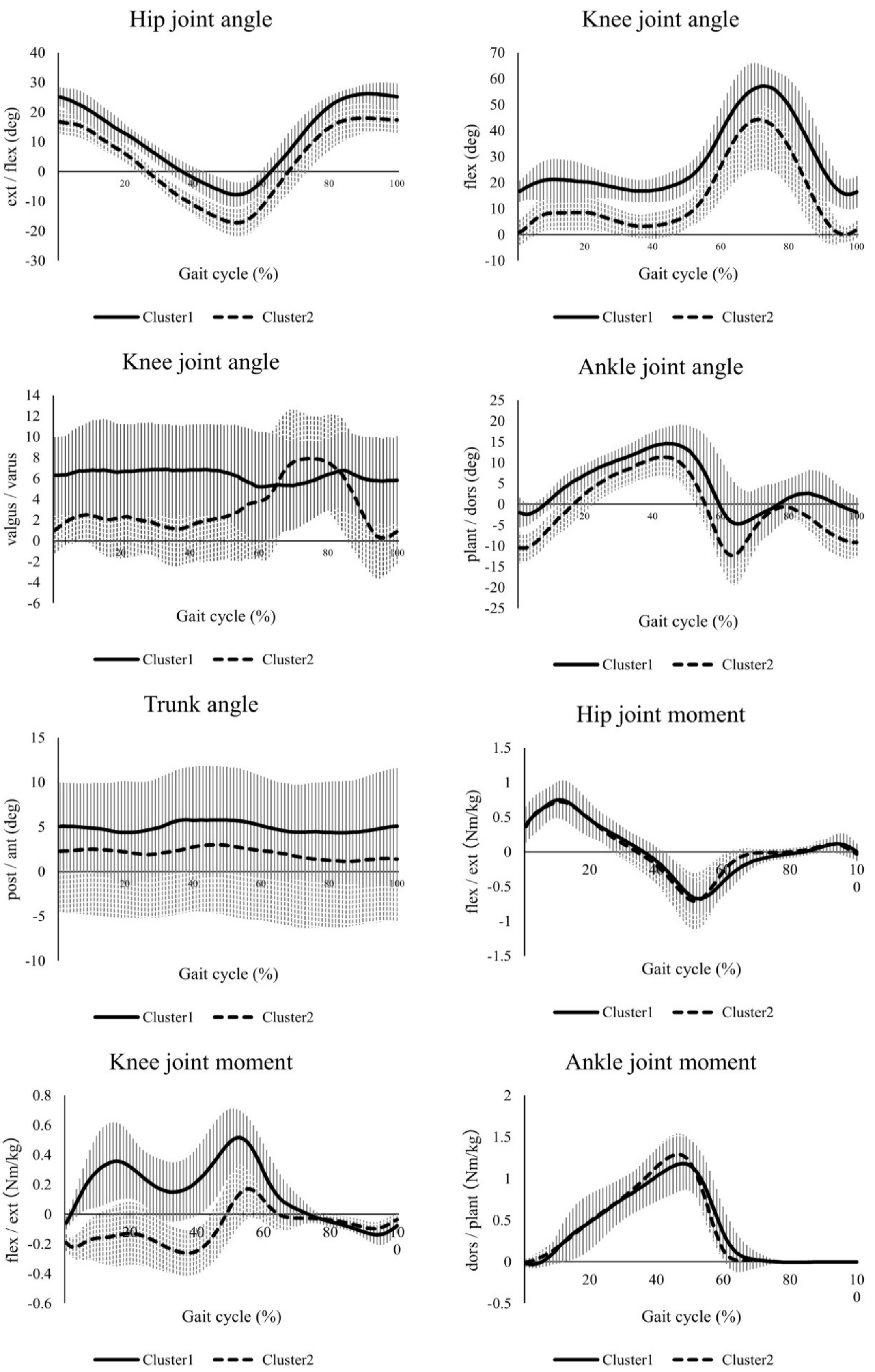

Figure 2. Change in joint angle and moment during one gait cycle

Table 3. Comparison of physical function between two clusters

	Cluster1 (*n*=12)	**Cluster2 (*n*=11)**	***p***
Muscle strength (kgf/kg)			
Hip joint flexion	0.27 ± 0.08	0.29 ± 0.09	.538
Hip joint extension	0.30 ± 0.09	0.35 ± 0.12	.409
Knee joint extension	0.34 ± 0.12	0.37 ± 0.09	.402
Ankle joint plantar flexion	0.22 ± 0.08	0.31 ± 0.05	.003
Hip joint JOA score (point)			
Total	86.0 ± 11.5	96.8 ± 3.1	.014
Pain	96.4 ± 9.4	99.4 ± 1.9	.528
Range of motion	92.7 ± 11.1	99.1 ± 2.3	.121
Walking ability	63.8 ± 26.0	90.5 ± 10.8	.011
ADL	80.8 ± 15.6	95.5 ± 9.3	.014
Knee joint JOA score (point)			
Total	80.8 ± 12.4	93.2 ± 12.1	.009
Pain / walking ability	75.7 ± 26.9	97.7 ± 5.4	.050
Pain / stair climbing ability	82.5 ± 14.8	97.3 ± 6.5	.010
Flexion angle and ankylosis/high contracture	78.6 ± 7.5	84.4 ± 29.6	.019
Swelling	100.0 ± 0.0	100.0 ± 0.0	1.00
Ankle joint JOA score (point)			
Total	80.3 ± 11.0	92.1 ± 7.6	.007
Pain	100.0 ± 0.0	98.9 ± 3.8	.296
Deformation	89.7 ± 17.9	97.4 ± 8.5	.147
Range of motion	74.2 ± 21.1	85.9 ± 22.9	.105
Instability	95.0 ± 17.3	100.0 ± 0.0	.338
Walking ability	55.0 ± 22.8	81.8 ± 14.0	.005
Strength	53.3 ± 28.7	74.5 ± 32.4	.101
Paresthesia	66.7 ± 40.3	90.1 ± 13.8	.219
ADL	50.0 ± 17.1	80.0 ± 22.8	.004

Table 4. Comparison of frailty and sarcopenia and complications between two clusters

	Cluster1 (*n*=12)	**Cluster2 (*n*=11)**	***p***
Sarcopenia (*n*)			
Severe sarcopenia	3	0	
Sarcopenia	3	4	.204
No sarcopenia	6	7	
J-CHS score (*n*)			
Frail	3	2	
Pre-frail	7	5	.560
Robust	2	4	
CCI	5.42 ± 2.35	5.36 ± 2.46	.958
A-stage index	4.83 ± 4.13	1.64 ± 3.04	.062

3.2. Comparison of Physical Function between the Two Clusters (Table 3)

In lower limb muscle strength, ankle plantar flexion in Cluster 1 (0.22±0.08 kgf/kg) was significantly lower than that in Cluster 2 (0.31±0.05 kgf/kg) (p=.003).

The total hip JOA score in Cluster 1 (86.0±11.5) was significantly lower than that in Cluster 2 (96.8±3.1) (p=.014). Cluster 1 was also significantly lower in walking ability (p=.011) and ADL (p=.014). The knee joint JOA score was significantly lower in Cluster 1 (80.8±12.4 points) than that in Cluster 2 (93.2±12.1 points) (p=.009). Cluster 1 was significantly lower in pain, stair climbing ability (p=.010), and flexion angle and ankylosis/high contracture (p=.019) than Cluster 2. The total foot JOA score in Cluster 1 (80.3±11.0) was significantly lower than that in Cluster 2 (92.1±7.6) (p=.007). Cluster 1 was also significantly lower in walking ability (p=.005) and ADL (p=.004) than Cluster 2.

3.3. Comparison of Frailty and Sarcopenia between the Two Clusters (Table 4)

In AWGS2019, there was no significant difference between the two clusters, with Cluster 1 having 3 severe sarcopenia and 3 sarcopenia cases and Cluster 2 having 0 severe sarcopenia and 4 sarcopenia cases. In J-CHS, Cluster 1 had 3 frail and 7 prefrail cases and, Cluster 2 had 2 frail and 5 prefrail cases, with no significant difference between the two clusters (p=.560).

3.4. Comparison of Dialysis-Related Complications between the Two Clusters (Table 4)

For CCI, Cluster 1 was 5.42±2.35 and Cluster 2 was 5.36±2.46, with no significant difference between the two clusters (p=.958). For the A-stage index, Cluster 1 (4.83±4.13) was not significantly different from that in Cluster 2 (1.64±3.04) (p=.062).

4. Conclusion

4.1. Basic Information and Physical Function Characteristics of Each Cluster

Cluster 1 was characterized by longer hemodialysis duration, more severe dialysis amyloidosis, knee joint pain, ankle plantarflexion weakness, and lower extremity joint dysfunction than that observed in Cluster 2. Cluster 2 was characterized by a short duration of hemodialysis and minimal lower extremity joint dysfunction compared to Cluster 1.

The factor affecting the gait classification of hemodialysis patients in this study was a decline in joint function. These declines in joint function may be related to dialysis amyloidosis, as Cluster 1 had a higher A-stage index and a longer duration of dialysis. Carpal tunnel syndrome, a typical and first-episode manifestation of dialysis amyloidosis, has been associated with prolonged hemodialysis duration and a high incidence of the disease in many cases [6], [20], [21].

Pain and limited range of motion of the knee joint were also observed in Cluster 1. Blood β2-microglobulin, a precursor protein of dialysis amyloidosis, is preferentially deposited in osteoarticular sites, and amyloid synovitis is present in various joints in patients undergoing long-term hemodialysis, with thickening of tendons and lesions of bone erosions [22]. Furthermore, hemodialysis itself is an inflammatory stimulus that induces cytokine production and complement activation [23]. For this reason, 76.4% of hemodialysis patients present with musculoskeletal disorders such as osteoarthritis and pain [24]. Furthermore, knee joint pain has been a major cause of decreased ADL in patients with dialysis amyloidosis [20], and, in Cluster 1, knee joint pain and limited range of motion affected walking.

Decreased ankle plantarflexion muscle strength was also considered a factor affecting hemodialysis patients' gait classification in this study. Ankle plantar flexor muscle strength is related significantly to walking ability, including balance and transfer of propulsive force to the floor during gait. It has been reported that hemodialysis patients have decreased physical activity, muscle strength, and walking velocity, with significant muscle atrophy and increased non-contractile tissue [25].

4.2. Characteristics of Walking in Each Cluster

Cluster 2, which had a shorter duration of hemodialysis than Cluster 1, had joint angles and joint moment patterns during gait that were similar to normal gait, which preserved walking velocity. However, Cluster 2 was characterized by a smaller moment of knee joint extension during the stance phase. This is because the knee joint flexion moment and the floor reaction force vector exit the front surface of the knee joint, exerting an external force on the knee joint in the hyperextension direction. In the stance phase, the knee joint flexion moment and the floor reaction force vector were caused by a decrease in the ankle dorsiflexion angle due to a decrease in soleus muscle extensibility and a decrease in knee joint extensor muscle strength. The soleus muscle prevents the lower leg from tilting forward too much from initial contact to mid-stance and generates the greatest ankle plantarflexion moment during walking from mid-stance to terminal stance, producing forward propulsion. It has been reported that hemodialysis patients have decreased physical activity, muscle strength, and walking velocity, with significant muscle atrophy and increased non-contractile tissue [25]. Cluster 2 showed higher ankle plantarflexion muscle strength than Cluster 1 but lower muscle strength, suggesting that the ability of the soleus muscle to contract and relax may be impaired in Cluster 2. Cluster 2 also showed decreased knee joint extensor strength compared to Cluster 1. Cutoff values for knee extension muscle strength have been reported as 1.4 Nm/kg for independent standing and moving movements and 1.2 Nm/kg for falls [26]. Therefore, the high tension in the stance phase caused by weakness of the soleus muscle and the associated loss of extensibility, as well as weakness of the quadriceps muscle, which is important for knee joint control in the stance phase, leads the lower leg backward in the stance phase, generating a knee joint flexion moment and causing the floor reaction force vector to exit the front of the knee joint. If the knee joint flexion moment occurs throughout the stance phase and external forces are constantly exerted in the direction of knee joint hyperextension, soft tissues behind the knee joint may be stretched or compressed, resulting in blood retention, which may lead to pain and inflammation of the posterior knee joint.

The gait of Cluster 1 had been on hemodialysis for a longer duration than Cluster 2, was an inflection at the knee joint, ankle joint, and trunk, and the ankle joint plantarflexion moment in Cluster 1 was small at toe-off, resulting in inadequate kicking and a reduced walking rate and walking velocity. The walking velocity of hemodialysis patients was lower than that of the same age group, with a reported walking velocity of 1.01 m/s [27] and a walking rate of 100.1 ± 12.6 steps /min [28]. Although the subjects in this study were ≥60 years old, they were able to walk independently without assistance (i.e., cane), indicating that their walking ability was relatively preserved. However, Cluster 1 had a slower walking velocity and a lower rate than Cluster 2. The decrease in walking velocity is related to the decrease in step length and walking rate. For this reason, no difference was observed between the step lengths of the two clusters, but, in Cluster 1, the decrease in walking rate resulted in a decrease in walking velocity.

Cluster 1 showed excessive knee flexion from initial contact to the terminal stance. When the knee joint flexion angle at initial contact is increased, the knee joint cannot step with the heel, and the knee joint flexion moment cannot be fully exerted. During the loading response, the ankle dorsiflexion moment and ankle plantarflexion angle were small in Cluster 1 because the heel rocker was not fully activated. Therefore, to perform the loading response with excessive knee flexion, the knee joint extension moment was increased to provide stable weight-bearing and forward body movement. At the terminal stance, the knee joint was slightly extended, but the knee joint was excessively flexed, so the hip joint extension angle became small, and a knee joint extension moment appeared. In addition to small hip and knee extension, the ankle plantarflexion moment was also small, which may have reduced forward acceleration and decreased the walking rate.

Excessive knee flexion during the stance phase, as seen in Cluster 1, is similar to the gait of patients with knee osteoarthritis. It has been reported that the gait of patients with knee osteoarthritis is accompanied by increased knee joint internal rebound moment, decreased knee joint flexion moment, and increased knee joint flexion angle during walking, as well as decreased walking velocity [29]. However, in Cluster 1, the knee joint varus angle during the stance phase is not large. There was no increase in knee joint varus angle during initial contact, the loading response, and the terminal stance, and no evidence of lateral thrust. None of the subjects reported edema or swelling in the swelling item of the knee joint JOA score. None of the patients had an obvious deformity on the anterior plane. It is possible that the pain is related to the limited range of motion of the knee joint rather than to a pain-evading gait due to medial compartment failure, as is seen in the gait of patients with knee osteoarthritis. Cluster 1 had lower scores than Cluster 2 on the knee JOA score items of flexion angle and ankylosis/severe contracture and pain. In terms of knee pain, the score for the ability to ascend and descend stairs in the knee joint JOA score was higher than that for the ability to walk, and there was no worsening of pain when ascending or descending stairs. Therefore, excessive flexion of the knee joint during the stance phase in Cluster 1 appeared as an escape gait for pain in the posterior aspect of the knee joint rather than pain related to the patellofemoral joint in the anterior aspect of the knee joint, which is said to increase pain when ascending and descending stairs.

Posterior knee pain in hemodialysis patients is common. However, although it has been reported that knee joint pain in hemodialysis patients is an important issue, it has not been clarified which tissues are responsible for the pain and the effect of mechanical stress during movement. During the short hemodialysis duration, as in Cluster 2, knee joint flexion moments occur throughout the stance phase, and external forces are always exerted in the direction of knee joint hyperextension. At this stage, knee joint pain is not a major problem, but as the hemodialysis duration lengthens, the soft tissues behind the knee joint stretch and continue to be blocked by pressure, which may lead to pain and inflammation in the posterior knee joint. It has been reported that blood β2-microglobulin, a precursor protein substance of dialysis amyloidosis, occurs in the cartilage in the early stages and then extends to the joint capsule and synovium, especially during the short hemodialysis duration [30]. Blood β2-microglobulin is also preferentially deposited in osteoarticular sites. In patients undergoing long-term hemodialysis, amyloid synovitis is present in various joints, with thickening of tendons and lesions of bone erosion [22]. Therefore, mechanical stress in the direction of hyperextension of the knee joint is likely applied to the posterior surface of the knee joint from a short duration of hemodialysis, causing stretching of the soft tissues and continued hemorrhage due to pressure, resulting in pain and inflammation of the joint capsule and synovial membrane at the posterior surface of the knee joint. The pain in the posterior knee joint and the organic changes in the soft tissues may have resulted in decreased flexibility and extensibility, leading to limited knee joint extension during gait.

4.3. Rehabilitation Approach

The gait of hemodialysis patients was characterized by joint angles and moments of the knee joint in the stance phase. Knee joint pain and limited range of motion can restrict walking and ADL, and knee joint replacement surgery may be considered. However, since the prognosis after knee replacement surgery is poor in hemodialysis patients [31]–[34], aggressive physical therapy aimed at preventing the severity of the disease is necessary from the early stage.

In physical therapy for patients with knee osteoarthritis, who have similar gait characteristics as hemodialysis patients, a strategy to reduce mechanical stress in the knee joint on the frontal plane associated with knee joint deformity is applied [35]. However, the treatment strategy for hemodialysis patients is usually different because there is no obvious deformity in the frontal plane. The two clusters were different in terms of angles and moments of the knee joint in the stance phase. The differences in hemodialysis history and dialysis amyloidosis between the two clusters suggest that treatment strategies should be considered in hemodialysis therapy.

In the early phase of hemodialysis, it is important to maintain ankle dorsiflexion flexibility, ankle plantar flexor strength, quadriceps strength, general muscle strength, and joint range of motion, and to maintain ankle joint locker and knee joint control in the stance phase. This will prevent the generation of external forces in the direction of hyperextension of the knee joint during the stance phase, thereby avoiding the occurrence of pain in the posterior aspect of the knee joint. However, aging and hemodialysis therapy cannot be stopped. Thus, it is important to actively work to reduce pain in the posterior knee joint and maintain or improve the range of motion of the knee joint and ankle plantarflexion muscle strength, depending on the degree of muscle weakness, loss of joint range motion, and severity of hemodialysis amyloidosis. In addition, it is important to acquire a gait style that reduces mechanical stress on the posterior knee joint and maintains gait stability and propulsive force in the stance phase, leading to maintenance of walking rate and velocity. Stable gait also leads to the prevention of falls and the maintenance of ADL.

The findings of this study have to be seen in the light of limitations. This study is a pilot study and has a small number of subjects. A too-small sample makes it difficult to identify important relationships from the data. It is recommended that it be replicated with a larger group of participants.

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