Master's Thesis
석사 학위논문

Classification of Gait Type in Hip Osteoarthritis Patients using Principal Component Analysis and Gaussian Mixture Model

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Robotics Engineering. The study was conducted in accordance with Code of Research Ethics[1]

12. 18. 2020

Approved by

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[1] Declaration of Ethical Conduct in Research**:** I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

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Hayoon Lee

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

11. 27. 2020

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ABSTRACT

This paper proposes and compares two approaches that can identify different gait types of patients with hip osteoarthritis (OA) quantitatively using machine learning techniques. One is a simple and intuitive method that does not need clustering steps, and the other is a more detailed classification method that subdivides the gait classification results of the first method.

Force plate measurements of 22 patients with hip OA and 18 healthy subjects without surgical history were collected and analyzed using principal component analysis (PCA) and Gaussian Mixture Model (GMM) to identify different types of gait. The physical meanings of the identified gait types are explained using the latent features of gait obtained from PCA and muscle forces calculated using OpenSim.

The approaches will not only be useful for understanding the gait patterns of patients with hip OA but also will be applicable in analyzing different types of gait other than those of patients with hip OA.

Keywords: Gait classification, Principal component analysis, Gaussian mixture model, OpenSim

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I Introduction

Hip osteoarthritis (OA) is a prevalent chronic musculature disease that limits movement and accompanies pain [1][2]. The joint impairment and pain associated with the disease often affect patients' gait patterns suffering from hip OA [3]. Therefore, understanding the various effects of the disease on gait is necessary for the appropriate care of the disease [4][5][6].

Various features of the gait of hip OA patients were studied. Some research studied the kinematic features of the gait of patients suffering from hip OA using instruments such as motion capture systems [7][8][9]. Joint movements of the hip, knee, and ankle joints and other kinematic features such as stride and gait velocity of patients with hip OA and healthy subjects are shown to be different [7][10][11]. Kinetic characteristics, including joint moments and ground reaction forces of patients with hip OA and healthy subjects, were compared and analyzed using motion capture systems and force plates [12][13][14]. Differences in muscles of patients with hip OA and healthy subjects were also studied. For example, muscle sizes measured using magnetic resonance imaging (MRI) and muscle activation periods obtained from electromyography (EMG) of hip OA patients are shown to be different from those of healthy subjects [15][16][17].

Although numerous studies provide detailed information on the effects of the hip OA on gait, one limitation is that the findings are fragmentary. In other words, the kinematic, kinetic, and muscular features of gait are superficially shown, lacking the composite discussions that encompass various features of the gait of hip OA patients. This is because human gait is a complex motion [18] with high-dimensional and variable measurements [19][20][21]. Several techniques, such as principal component analysis (PCA), are used to analyze the gait data to overcome the above limitation of previous studies. PCA is a dimension reduction method that reduces the dimension of the given data by deriving latent features of the given data [22]. Multidimensional and correlated gait data can be transformed into a set of low-dimensional and uncorrelated data using PCA [23][24][25]. Since the appropriate reduction of gait data is necessary for an effective understanding of gait, the technique is frequently used for analyzing gait measurements [22].

An additional limitation of the previous studies on the gait of hip OA patients is that a majority of research on the gait diagnosis of the disease focus on the severity of the disease [16][26], neglecting the possibility of the existence of various types of gait impairment induced by the disease. To overcome the problem, some studies tried to identify different types of gait dysfunction using clustering techniques [27] but did not clarify quantitative standards that can distinguish different types of gait other than the degree of severity.

Moreover, most of the diagnosis of hip OA is made through subjective and qualitative methods such as questionnaires [28][29] and radiography [30]. Lastly, the data measurement methods present

some limitations, especially for the measurement of muscle forces. To this end, wearable sensors such as electromyography (EMG) and inertial sensors are used to obtain various gait data [31]. However, attaching sensors to the human body for gait analysis can be inconvenient and disturb the natural human movement.

Thus, this paper proposes two approaches that can quantitatively identify different gait types of patients with hip OA using machine learning techniques. The important features of the approaches are explained and compared. Then, the features and physical interpretations of the identified gait types are explained with the gait types' force plate measurements and muscle forces. The overall process of the proposed approach is shown in Fig. 1.

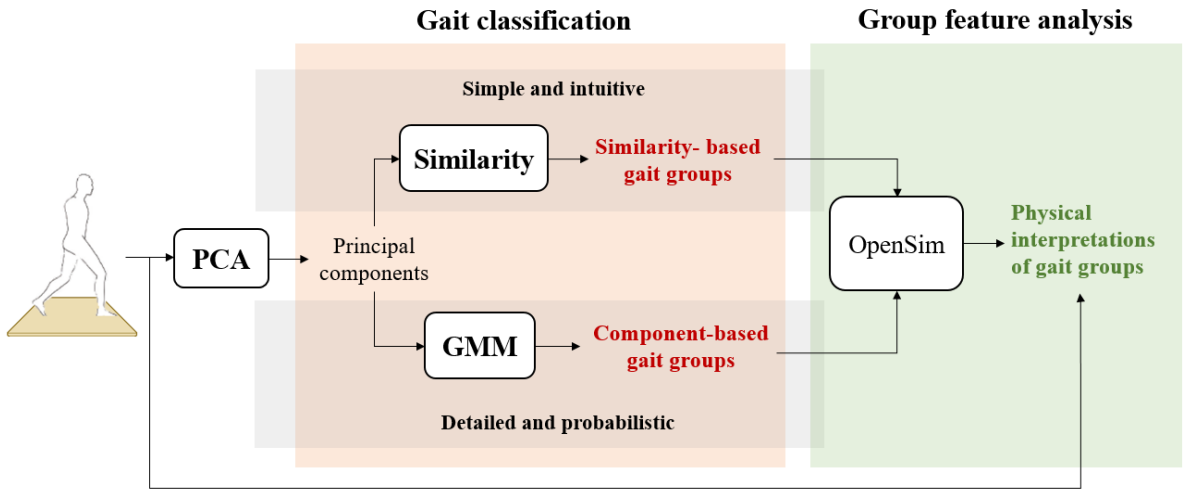

Figure 1: The overall process of the proposed approach of gait type classification of hip OA patients.

II Method

2.1 Subjects

The gait experiments were conducted on 22 hip OA patients (12 women and 10 men, age : 56±13 years, weight : 67±9kg, height : 164±6cm) and 18 healthy subjects (9 women and 9 men, age : 56±9 years, weight : 64±10kg, height : 163±6.7cm) with no previous surgery history. The subject information of the subjects that participated in the experiments are shown in Table 1.

2.2 Instrument

The gait experiments were done using force plates (2EA, AMTI, Watertown, MA, USA), and gait data analysis was done using Python (version 3.6.7, 64-bit) with NumPy 1.16.3, matplotlib 3.0.1, and pandas 0.23.4 packages.

Hip OA patients	Sex	Age	Height (cm)	Weight (kg)	gait velocity (m/s)	stride length (m)	Affected leg
Subject 1	male	52	176	70.0	0.9	0.5	left
Subject 2	female	69	153	52.0	0.8	0.3	right
Subject3	female	71	157	60	0.4	0.3	left
Subject4	female	45	157	74	0.6	0.3	left
Subject5	female	71	144	52.1	0.7	0.4	right
Subject6	female	61	164	64	0.6	0.3	left
Subject7	female	46	156	78	0.6	0.3	left
Subject8	female	86	156	66	0.4	0.3	right
Subject9	female	48	164	66	0.7	0.4	left
Subject9	female	39	158	61	0.5	0.3	right
Subject10	male	61	174	74.8	0.5	0.3	right
Subject11	male	67	168	67.6	0.6	0.4	left
Subject12	male	49	170	77.2	0.8	0.5	left
Subject13	male	61	163	79.7	0.5	0.3	left
Subject14	female	60	155	49	0.7	0.4	right
Subject15	male	46	155	78.4	0.9	0.5	right
Subject16	male	59	166	67.7	0.8	0.5	right
Subject17	male	44	183	60.2	0.6	0.4	left
Subject18	female	62	150	60.7	0.4	0.3	left
Subject19	male	38	170	76	0.9	0.5	left
Subject20	male	51	164	73	0.7	0.4	left
Subject21	male	59	163	65	0.7	0.4	left
Subject22	male	35	173	73.7	0.8	0.5	right
Average		56±13	163±67	67±9	0.7±0.2	0.4±0.1	
Healthy control	Sex	Age	Height (cm)	Weight (kg)	gait velocity (m/s)	stride length (m)	
Subject23	male	48	178	78.1	0.5	0.3	
Subject24	male	54	167	68.36	0.7	0.3	
Subject25	male	75	166	65	0.9	0.5	
Subject26	female	75	160	60.5	1.0	0.5	
Subject27	female	47	161	52.55	1.1	0.5	
Subject28	male	58	168	79.5	1.3	0.5	
Subject29	female	51	154.5	49.5	1.0	0.5	
Subject30	female	51	163	58.8	0.8	0.4	
Subject31	female	57	162	65.6	1.0	0.5	
Subject32	female	55	157	48.6	0.5	0.3	
Subject33	male	62	161	58.3	1.2	0.5	
Subject34	female	57	158	53	1.1	0.5	
Subject35	female	60	163.5	61.4	1.0	0.5	
Subject36	male	51	163	77.2	1.0	0.5	
Subject37	female	49	170	63.8	1.2	0.5	
Subject38	male	58	171	65.2	0.9	0.5	
Subject39	male	64	160	83	0.7	0.4	
Subject40	male	32	170	68	0.8	0.3	
Average		56±9	164±6	64±10	0.9±0.2	0.4±0.1	

Table 1: The subject information of patients with hip OA and healthy subjects who participated in the gait experiment.

2.3 Experiment protocol

To measure the natural gait of subjects, the subjects walked on the floor before the gait experiment to induce natural movements. Then the subjects walked on the force plates several times, as shown in Fig. 2. Wooden blocks with heights that are the same as the force plates were placed around the force plates for appropriate gait measurements. About 7 trials per subject in which each leg stepped on the force plates were selected for data analysis.

Figure 2: The gait experiment using force plates.

2.4 Measured variables

The ground reaction force (GRF) and the moment of subjects during the stance phase were obtained from the gait experiments. The stance phase is the gait phase from heel strike until toe off [32][33] as in Fig. 3. For the accurate data analysis, the directions of GRF and moment of the left and right foot were aligned in the same direction. The resulting gait measurements are shown in Fig. 4. In the figure, the blue line and red line indicate the average of the gait measurements of healthy subjects and hip OA patients, respectively, and the standard deviation of the gait measurements are shown in lighter colors.

2.5 Institutional review board

Before the experiment, the subjects signed consent forms approved by the university Institutional Review Board. This study followed the policy statement with respect to the Declaration of Helsinki.

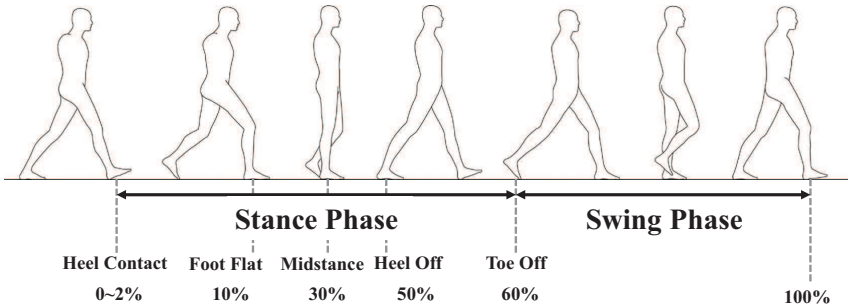

Figure 3: The gait phase description.

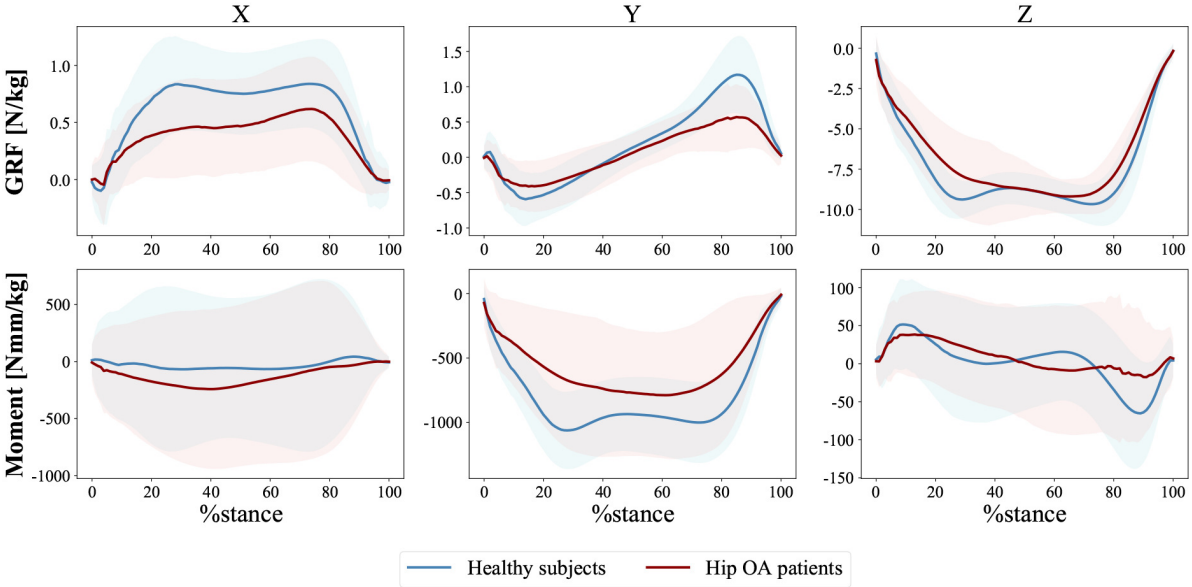

Figure 4: The gait measurements of healthy subjects and patients with hip OA from force plates.

2.6 Dimension reduction methods

In previous studies, classification or identification of different types of pathological gait was frequently made using statistical analysis and machine learning techniques, including support vector machines or artificial neural networks [34][35][36]. Although statistical analysis yields reliable results, machine learning techniques are more advantageous since it is less sensitive to outliers and noise and automated classification is possible [34].

When clustering or classifying different types of gait using machine learning techniques, some studies used one clustering techniques to differentiate different types of gait [27]. In contrast, others first used the dimension reduction method to either reduce the dimension or extract significant features of the original data and then applied clustering or classification techniques [36][37].

For analyzing and understanding complicated features of gait, reducing the dimension of gait data is known to be important [22] since human gait is a complex motion that yields correlated and multivariate measurements [18][19][20][21].

One of the dimension reduction techniques widely used for gait analysis is principal component analysis [38]. PCA is a linear and deterministic dimension reduction method that obtains the latent features of the given data by calculating orthogonal eigenvectors from the covariance matrix of the given data [22]. The eigenvectors, which are called principal components, describe the directions where the data variance is the largest [38]. Using PCA, the high-dimensional and correlated gait data can be converted into low-dimensional and uncorrelated set of data [23][24][25]. The principal components become the axes of the reduced dimension [38][39][40].

Non-negative matrix factorization (NMF) is a similar method that can be used for dimension reduction. NMF is a linear dimension reduction method applied to non-negative data [41][42]. NMF obtains latent features of given data by calculating basis vectors that are additive linear combinations of variables of the original data [42][43].

Other PCA-related methods include kernel PCA and probabilistic PCA (PPCA). Kernel PCA is a nonlinear and deterministic method that derives nonlinear principal components using kernel functions [44][45]. PPCA is a linear and probabilistic version of PCA known to be effective in dealing with missing data [46].

There are also numerous nonlinear and probabilistic dimension reduction methods. Generative topographic mapping maps the data from latent space to original space using a mixture of Gaussians [47]. The Gaussian process latent variable model (GPLVM) can be considered a generalized approach of PPCA which calculates the joint density of data points in latent and original coordinates [48].

Other dimension reduction techniques, such as Sammon mapping or Isomap, use the distance between data points to map the original data to lower dimension [48][49].

Since the goal is to classify different types of the gait of hip OA patients and identify the characteristics of the identified types, the classification and interpretation of gait data should be made in the latent space. Also, the gait measurements include the GRF and moment of anterior-posterior, medial-lateral, and vertical directions, which contain both positive and negative values. Thus, PCA, which is a linear and deterministic method, is selected to reduce the dimension of gait data for simple and intuitive interpretation of latent gait features with both positive and negative values.

Important latent features that describe the force plate data can be derived using PCA for a simple comparison between gait patterns of healthy subjects and patients with hip OA. Using PCA, complex, correlated, and multivariate high-dimensional data can be converted to the uncorrelated set of data in the low dimension defined by the principal components [38]. The principal components can also be calculated using singular value decomposition (SVD). The main difference between SVD and PCA is that SVD decomposes the original data that are centered and normalized to obtain the eigenvectors, whereas PCA decomposes the covariance matrix [50].

The SVD equation is as follows:

$$H = L\Sigma R^T \tag{1}$$

where matrix H is the given data, L is the left eigenvector matrix, Σ is the diagonal singular value matrix, and R is the right eigenvector matrix.

Given that the rows of matrix H are time instances (from 0% stance to 100% stance) and columns of matrix H are the types of collected data from the force plates, which are the GRF and moment in anterior-posterior, medial-lateral, and vertical directions, $L\Sigma$ becomes the matrix of principal components that capture time-dependent features of H (temporal component), and R becomes the matrix of principal components that capture time-independent, spatial features of H (spatial component) as in [51].

2.7 Similarity of gait patterns

The temporal and spatial components can be derived for all gait trials. Therefore, the similarity of principal components among different individuals can be calculated. To classify and distinguish the different gait patterns of hip OA patients, it is necessary to determine how similar the gait patterns are to one another.

The similarity of the temporal components (temporal similarity) can be calculated using the correlation coefficient and the similarity of the spatial components (spatial similarity) can be obtained using cosine similarities as in [51]. The equation for temporal similarity is as follows:

$$TS_{i,j,n} = cov(\lambda_n u_{i,n}, \lambda_n u_{j,n})/\sigma_{\lambda_n u_{i,n}} \sigma_{\lambda_n u_{j,n}} \tag{2}$$

where $TS_{i,j,n}$ indicates for the temporal similarity between the nth temporal components of ith and j^{th} gait trials, cov represents the covariance, $u_{i,n}$ stands for n^{th} temporal component of the ith gait trial, λ_n stands for the nth singular value, and $\sigma_{\lambda_n u_{i,n}}$ stands for the standard deviation of $\lambda_n u_{i,n}$. The equation for spatial similarity is as follows:

$$SS_{i,j,n} = v_{i,n} \cdot v_{j,n} / |v_{i,n}||v_{j,n}| \tag{3}$$

where $SS_{i,j,n}$ stands for the spatial similarity between the nth spatial components of the ith and j^{th} gait trials, $v_{i,n}$ stands for the nth spatial component of the ith gait trial, and $|v_{i,n}|$ stands for the magnitude of $v_{i,n}$.

The temporal and spatial similarities present how similar a gait trial is with another gait trial, but they do not explain how similar a gait trial is with the rest of the remaining gait trials. If most of the measures show high values, which means that most gait trials are similar to each other, it is possible to

assume that one type of gait is dominant compared with the other gait types rather than several types having an equal or similar degree of dominance. In that case, the mean of the similarity measures can be an index that can explain how similar a gait trial is with the other gait trials.

The similarity mean of a trial is the average of similarity measures obtained from comparing a trial with the rest of the trials. The equation for the temporal similarity mean is as follows:

$$TSM_{i,n} = (TS_{1,1,n} + TS_{1,2,n} + ... + TS_{1,M,n})/M \tag{4}$$

where $TSM_{i,n}$ stands for the temporal similarity mean of the nth temporal component of the ith gait trial, $TS_{i,j,n}$ stands for the temporal similarity between the nth temporal components of the ith and j^{th} gait trials, and M stands for the total number of gait trials. The equation for the spatial similarity mean is the following:

$$SSM_{i,n} = (SS_{1,1,n} + SS_{1,2,n} + ... + SS_{1,M,n})/M \tag{5}$$

where $SSM_{i,n}$ stands for the spatial similarity mean of the nth temporal component of the ith gait trial, $SS_{i,j,n}$ stands for the spatial similarity between the nth temporal components of the ith and j^{th} gait trials, and M stands for the total number of gait trials.

The gait characteristics can be explained using the degree of accordance of the gait to the corresponding principal components. In other words, the values of each gait trial in a low dimension defined by principal components (component scores) become the measures that explain the characteristics of each gait trial. The component scores can be obtained by projecting the original data to principal components [52].

2.8 Clustering methods

Clustering methods are a part of unsupervised learning [53]. One of the commonly used clustering methods is k-means clustering, which iteratively updates the centers of each cluster [53]. However, this method is known to be dependent on initial cluster centers [54]. Another clustering technique that is similar to k-means clustering is fuzzy k-means clustering. This method allows each element in the given data to belong to multiple different groups [55].

Probabilistic clustering is also possible through the Gaussian mixture model (GMM) [56]. GMM is a model-based clustering technique that uses probability density functions to cluster and model data [56]. The number of Gaussians in GMM can be selected with the Bayesian Information Criterion (BIC) algorithm, which calculates the optimal number of Gaussians by considering the trade-off between the fit and complexity of the model [27].

When analyzing and grouping gait patterns of each subject, one gait trial could belong to multiple

types of gait with different degrees of membership. Therefore, GMM should be used to cluster different types of gait affected by hip OA and identify the membership of each gait trial to the identified groups.

There are several methods to evaluate the validity of the clustering results. Dunn index evaluates the validity of the clustering algorithm through the minimum distance ratio between different clusters to the maximum distance inside a cluster [57]. Davies-Bouldin (DB) index calculates the dispersion of clusters using the distances between the cluster centers [57][58]. Silhouette score evaluates the cluster validity for each sample using the average of intra-cluster distance and the average of the distance to the nearest cluster of a sample [57][59].

Silhouette score has many advantages compared to other validation methods. First, silhouette scores can compute the validity of each sample as well as the validity of the full cluster results [57][59]. Also, silhouette scores are bounded within the values of -1 and 1, which allows objective comparison between the validity of clusters of different data [59]. Therefore, silhouette scores are used to calculate the validity of the clustering of gait types in this paper.

2.9 Muscle force estimation

Estimating muscle force during motion can provide valuable information necessary to understand the dynamical features of subjects during motion [60][61][62][63]. Therefore, lower limb muscle force of each gait trial were estimated to understand and evaluate the physical and dynamical features of the classified gait types.

One of the most common methods of muscle force estimation is using electromyography (EMG). EMG can record the muscle activity by either inserting needle electrodes into the muscle or attaching the instrument on the surface of the skin [64]. However, the main problem of using EMG is that the first method is an invasive method which is hard to apply during gait experiments and the second method cannot measure the activity of deep muscles [65][66][67].

Another method of estimating muscle force is using musculoskeletal simulators such as OpenSim and Anybody [68][69][70][71]. The musculoskeletal simulators can estimate muscle force through static optimization (SO) or computed muscle control (CMC) methods [72][73][74], which are the techniques that calculate muscle force through inverse dynamics and optimization [75][76][77][78] or through forward dynamics and iterative calculation [79][80][81]. From pretests, it was shown that the statistical difference of accuracy between SO and CMC were not significant. However, the calculation time of CMC was 41 times longer than SO. The difference in calculation time between the two algorithms is known to occur because CMC performs several integration calculations [82]. Another notable point is that CMC is more appropriate to estimate muscle force during motion with an acceleration since CMC estimates muscle force through the iterative calculation of motion data and SO estimates muscle force by minimizing the

Muscle names	Abbreviations	Muscle names	Abbreviations
gluteus medius	glut med	rectus femoris	rect fem
gluteus minimus	glut min	vastus medialis	vas med
semimembranosus	semimem	vastus intermedius	vas int
semitendinosus	semiten	vastus lateralis	vas lat
bicep femoris long head	bifemlh	medial gastrocnemius	med gas
bicep femoris short head	bifemsh	lateral gastrocnemius	lat gas
sartorius	sar	soleus	soleus
adductor longus	add long	tibialis posterior	tib post
adductor brevis	add brev	flexor digitorum longus	flex dig
adductor magnus	add mag	flexor hallucis longus	flex hal
tensor fasciae latae	tfl	tibialis anterior	tib ant
pectineus	pect	peroneus brevis	per brev
gracilis	grac	peroneus longus	per long
gluteus maximus	glut max	peronous tertius	per tert
iliacus	iliacus	extensor digitorum	ext dig
psoas	psoas	extensor hallucis	ext hal
quadriceps femoris	quad fem	erector spinae	ercspn
gemelli	gem	interior oblique	intobl
piriformis	piri	and external oblique	extobl

Table 2: The muscles calculated from OpenSim.

sum of squared muscle activation [83].

To understand the classified gait types' physical features, estimating lower limb muscle forces during gait, including the deep muscles, was necessary. Therefore, the CMC technique from OpenSim was used to estimate the muscle force of the lower limb during gait to understand the physical features of gait types.

The gait 2392 model from OpenSim (release 3.3), which is the most widely used gait model with validated accuracy [84][85], was used to calculate the lower limb muscle force during gait experiments. The gait model settings, which include muscle length, stiffness, location, maximum contraction velocity, and maximum metric force, were set to default values. The muscles divided into several sections (gluteus medius, gluteus maximus, gluteus minimus, vasti muscles, biceps femoris, and gastrocnemius) were combined using the root sum squares of each section. The estimated muscle force of each subject was divided by the subject's weight for the appropriate comparison of muscle forces between different subjects. The names and abbreviations of the muscles calculated from OpenSim for gait pattern analysis are shown in table 2.

III Result

3.1 Gait type classification using similarity of principal components

Since the dimension of the gait measurements of force plates is large, the principal components of force plate measurements of each subject during stance were obtained from PCA for the gait analysis of healthy subjects (healthy gait) and hip OA patients (affected-limb gait) in the reduced dimension. As a result,

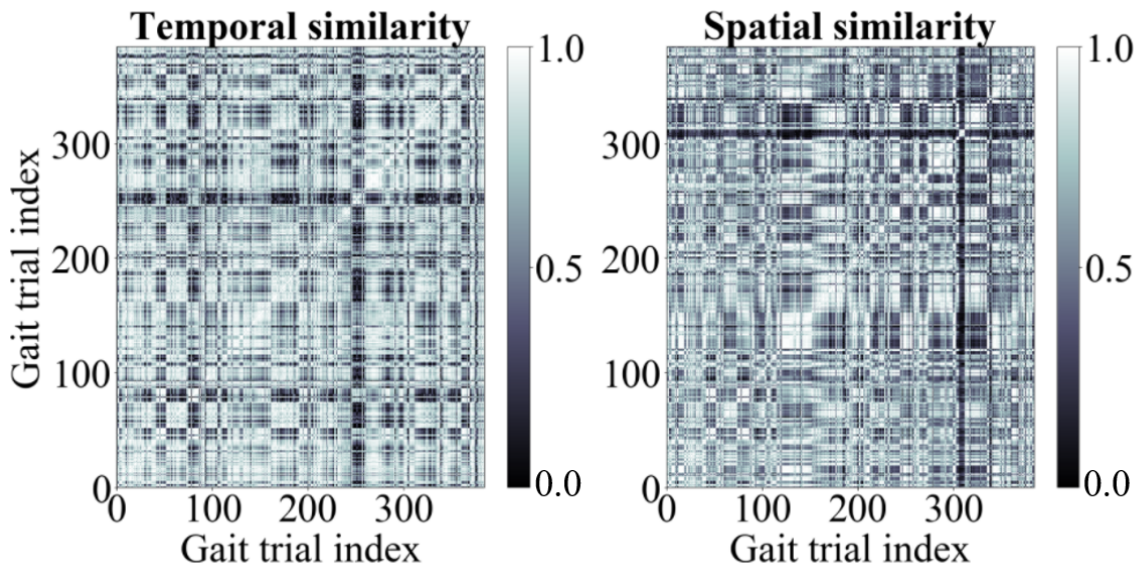

Figure 5: The pairwise similarities of the first principal components of each gait trial of the affected limbs of patients with hip OA and healthy subjects.

principal components with time-dependent gait features (temporal component) and time-independent gait features (spatial component) were obtained [51].

The temporal and spatial components with the largest eigenvalue, which are called the first temporal and spatial components, were used to compare healthy gait and affected-limb gait characteristics. By calculating the similarities of the first temporal and spatial components of gait trials, it is possible to compare and distinguish the healthy gait and affected-limb gait.

The similarities between the temporal and spatial components between different gait trials are shown in Fig. 5. In Fig. 5, gait trial pairs with high similarity are indicated in a bright color, and gait trial pairs with low similarity are indicated in dark color. The color bar explains the relationship between the similarity value and the corresponding color, in which the highest similarity value is 1, and the lowest similarity value is 0. The label ticks explain the indices of gait trials.

The temporal and spatial similarities explain the pairwise similarity of different gait trials, but the similarities cannot explain the similarity between one gait trial to the rest of the remaining gait trials. Therefore, similarity mean values for each gait trial were calculated for a better comparison between gait trials. The average of the temporal similarities was 0.70, and the average of the spatial similarities was 0.65, which implies that the similarity means can be used to explain the similarity of one gait trial to the rest of the gait trials quantitatively.

The similarity means of healthy gait and affected-limb gait are plotted in Fig. 6. From the similarity means, it is shown that the majority of healthy gait are similar to one another because 96.36% of the healthy gait had the temporal and spatial similarity mean over 0.5. However, the similarity means of affected-limb gait showed that several affected-limb gait trials were different from the other affected-limb

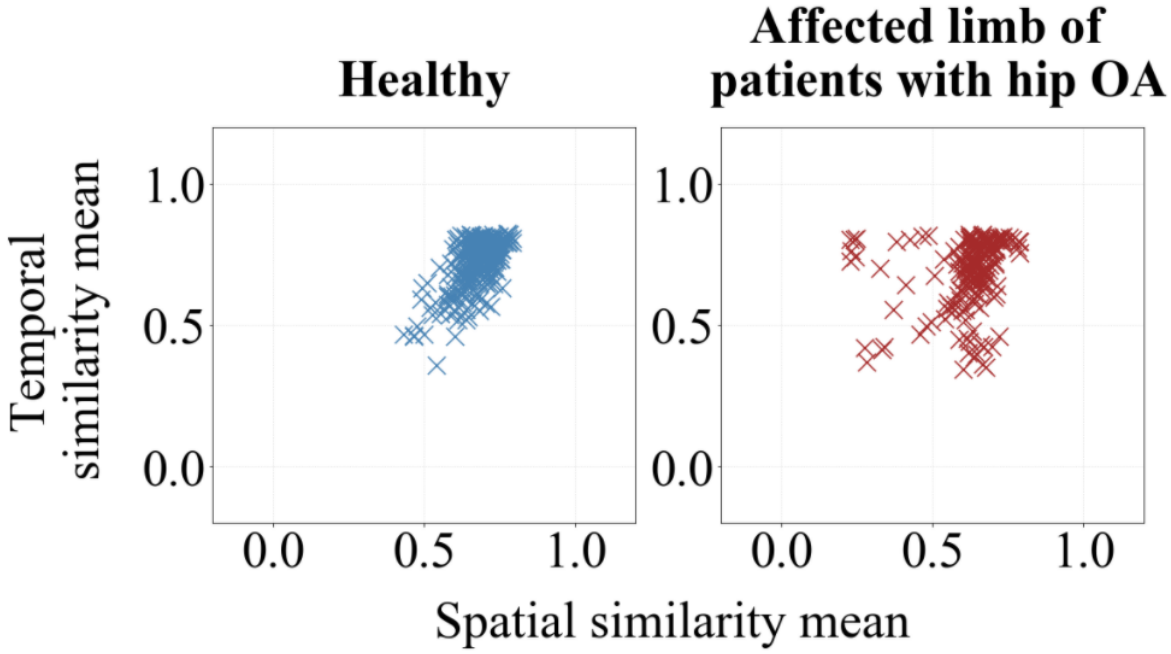

Figure 6: Temporal and spatial similarity mean values of healthy subjects and affected limbs of hip OA patients.

gait trials.

Therefore, it is shown that the affected-limb gait can be grouped into different types with the temporal and spatial similarity means. The temporal and spatial similarity means of 0.5 were used to quantitatively group the affected-limb gait because the value can group healthy gait into approximately single type and divide the affected-limb gait into several different types.

The affected-limb gait can be divided into 4 similarity-based groups. The first group (group A) is the group of affected-limb gait with temporal and spatial similarity means over 0.5, which 79.27% of the affected-limb gait belongs to this group. The second group (group B) is the group of affected-limb gait with temporal similarity mean over 0.5 but spatial similarity mean under 0.5, and 8.54% of the affected-limb gait belong to this group. The third group (group C) is the affected-limb gait group with temporal and spatial similarity means under 0.5, and 3.66% of the affected-limb gait belongs to this group. The fourth group (group D) is the group of affected-limb gait with temporal similarity mean under 0.5, but spatial similarity mean over 0.5, and 8.54% of the affected-limb gait belong to this group.

3.2 Gait type classification using Gaussian Mixture Model

Using GMM, different gait patterns can be distinguished from each gait trial's temporal and spatial components without the need to calculate the similarity means. The first principal components of each gait trial were used in the clustering process. The optimal number of clusters needed to cluster different gait types were selected through the BIC algorithm. For the gait trials of healthy subjects and patients

with hip OA, 5 was chosen to be the optimal number of Gaussians to cluster the spatial components, and 2 was chosen to be the optimal number of Gaussians to cluster the temporal components.

The clustering results of spatial components of healthy subjects are shown in Fig 7. In Fig 7, the blue dots indicate the values of the spatial components, and black dots indicate the center positions of each Gaussian. The clustering results of spatial components of patients with hip OA are shown in Fig 8. In Fig 8, the red dots indicate the values of the spatial components, and black dots indicate the center positions of each Gaussian. The mixture model results show that the gait trials of both healthy subjects and patients with hip OA can be distinguished into 5 distinct types with the values of spatial components.

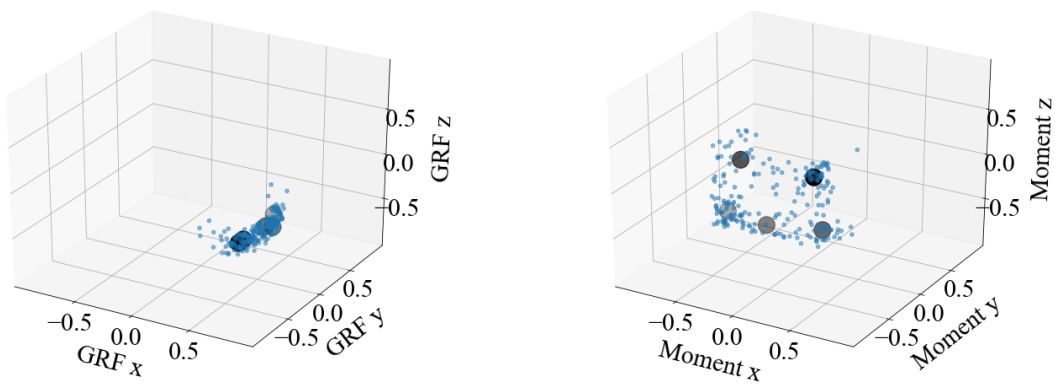

Figure 7: Gaussian mixture model of the spatial components of healthy subjects.

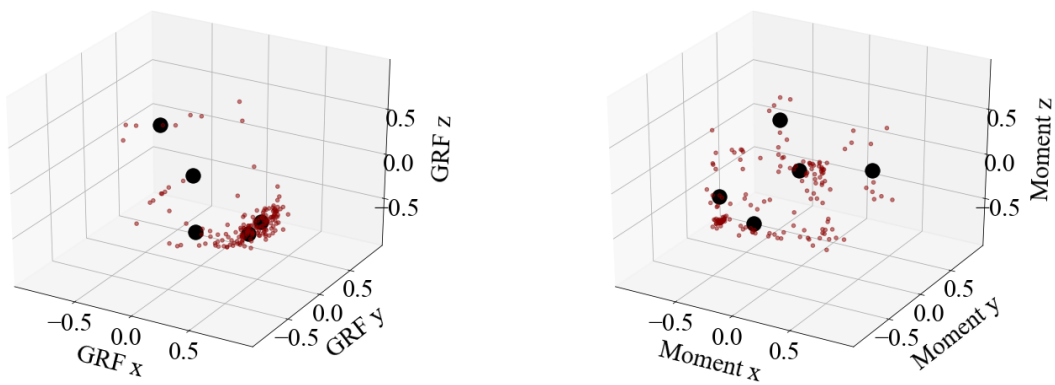

Figure 8: Gaussian mixture model of the spatial components of patients with hip OA.

The weights and center positions of each Gaussian of the spatial components of healthy subjects and patients with hip OA are shown in table 3 and table 4. The weights of Gaussians indicate the proportion of the gait trials comprised in the Gaussians, so large weight indicates that the Gaussian or gait type is

Features	Gaussian 1	Gaussian 2	Gaussian 3	Gaussian 4	Gaussian 5
Weights	0.24	0.28	0.17	0.14	0.17
GRF x	0.48	0.5	0.49	0.53	0.47
GRF y	-0.19	0.12	-0.28	0.18	0.3
GRF z	-0.49	-0.5	-0.48	-0.53	-0.47
Moment x	-0.36	0.37	-0.26	-0.01	0.4
Moment y	-0.49	-0.46	-0.46	-0.51	-0.38
Moment z	-0.27	0.3	0.31	-0.31	-0.31

Table 3: The weights and Gaussian center positions of the spatial GMM of healthy subjects.

Features	Gaussian 1	Gaussian 2	Gaussian 3	Gaussian 4	Gaussian 5
Weights	0.33	0.08	0.06	0.04	0.49
GRF x	0.46	0.19	-0.27	-0.32	0.44
GRF y	-0.08	-0.41	0.35	-0.06	0.15
GRF z	-0.49	-0.38	-0.27	0.48	-0.48
Moment x	0.25	-0.47	0.39	-0.47	-0.15
Moment y	-0.47	-0.43	0.4	0.48	-0.47
Moment z	0.35	-0.17	-0.05	0.24	-0.36

Table 4: The weights and Gaussian center positions of the spatial GMM of patients with hip OA.

more dominant than the other Gaussians or gait types.

The Gaussian center positions of temporal components of healthy subjects and patients with hip OA are shown in Fig 9 instead of the clustering results plotted with the temporal component values since the dimension of the temporal component is too large to visualize. In Fig 9, each dot represents the center position of Gaussians in each stance phase. The weight of the Gaussians of temporal components of healthy gait was 0.48 for Gaussian 1 and 0.52 for Gaussian 2. The weight of the Gaussians of temporal components of affected-limb gait was 0.66 for Gaussian 1 and 0.34 for Gaussian 2.

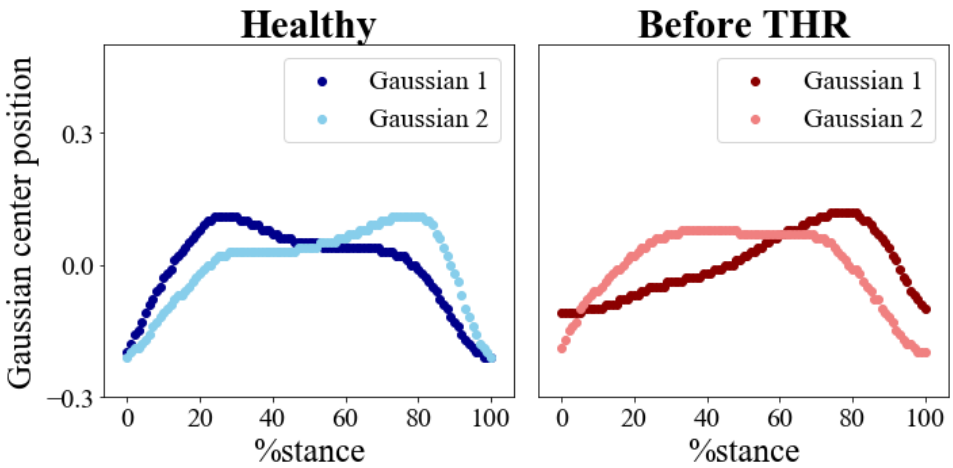

Figure 9: Gaussian center positions of temporal components of healthy subjects and patients with hip OA.

From the Gaussian mixture model clustering of the temporal and spatial components of healthy gait and affected-limb gait, it is shown that both healthy gait and affected-limb gait can be divided into 5 groups in the spatial aspects (spatial component-based groups) and 2 groups in the temporal aspects

(temporal component-based groups).

3.3 Muscle forces of the identified gait types

Force plate measurements and muscle forces of the classified gait types were analyzed to understand the classified gait types' physical interpretations and meanings. There were no significant differences in the force plate measurements of different gait groups for both similarity-based groups and component-based groups. This is assumed to be because the similarity-based groups and component-based groups are derived using the temporal and spatial components of gait trials, which are the latent features of gait obtained by reducing the dimension of the force plate measurements. Therefore, it is assumed that the similarity-based method and component-based method captured the different types of gait, which is not easily visible in the force plate measurements.

For the comparison of muscle forces of the similarity-based groups and component-based groups in spatial aspects, the maximum muscle force values of each gait trial during stance were calculated, and the significance in the difference of the maximum muscle force values between groups was analyzed through one-way analysis of variance (ANOVA). The average and standard deviation of the maximum muscle force values during stance of each similarity-based group are shown in table 5. The p-values of the maximum muscle force values during stance for different similarity-based groups are shown in table 6. The average and standard deviation of the maximum muscle force values of each spatial component-based group are shown in table 7. The p-values of the maximum muscle force values during stance for different spatial component-based groups are shown in table 8.

For the comparison of muscle forces of the similarity-based groups and component-based groups in temporal aspects, the maximum muscle force values of each gait trial during each stance phase were calculated, and the significance in the difference of the maximum muscle force values between groups was analyzed through one-way ANOVA. The calculation and comparison of muscle forces for the groups divided in the temporal aspect were separately made for each stance phase to determine the groups' phase characteristics and differences.

The average and standard deviation of the maximum muscle force values for all stance phases (heel contact, foot flat, mid-stance, heel off, toe off) of each similarity-based group are shown in table 9. The p-values of the maximum muscle force values during stance for different similarity-based groups are shown in table 10. The average and standard deviation of the maximum muscle force values for all stance phases of each temporal component-based group are shown in table 11. The p-values of the maximum muscle force values during stance for different similarity-based groups are shown in table 12.

Muscle	Healthy Mean (std)	Group A Mean (std)	Group B Mean (std)	Group C Mean (std)	Group D Mean (std)
glut med	12.97 (4.55)	9.91 (5.47)	7.55 (3.7)	8.29 (2.59)	9.74 (5.84)
glut min	5.12 (2.58)	3.74 (2.56)	2.29 (1.68)	2.22 (1.46)	4.02 (2.71)
semimem	4.94 (2.62)	3.78 (3.09)	3.09 (3.41)	1.8 (0.38)	9.49 (3.11)
semiten	1.74 (1.39)	1.64 (1.63)	0.84 (1.33)	0.74 (0.4)	3.46 (1.6)
bifemlh	4.25 (1.96)	3.83 (3.13)	3.03 (3)	1 (0.62)	7.9 (3.41)
bifemsh	7.54 (2.74)	7.07 (3.21)	5.85 (2.75)	5.48 (4.16)	8.74 (2.8)
sar	1.93 (0.76)	1.63 (0.86)	1.28 (0.74)	1.7 (1.31)	1.7 (1.09)
add long	3.29 (2.69)	3.58 (3.48)	2.16 (3.13)	2.15 (2.05)	5.93 (2.63)
add brev	2.38 (2.06)	2.52 (2.91)	1.44 (2.23)	0.47 (0.33)	4.55 (2.87)
add mag	2.85 (2.05)	2.99 (3.41)	1.46 (1.96)	0.76 (0.49)	5.27 (3.87)
tfl	2.88 (1.26)	2.22 (1.11)	1.67 (0.88)	2.25 (1.28)	1.94 (1.07)
pect	1.11 (1.04)	1.36 (1.59)	0.67 (1.07)	2.23 (2.59)	2 (1.51)
grac	0.58 (0.64)	0.64 (0.8)	0.3 (0.58)	0.17 (0.12)	1.31 (0.85)
glut max	6.18 (3.08)	4.9 (4.53)	2.99 (2.79)	1.16 (1.44)	7.16 (6.1)
iliacus	11.65 (17.33)	9.47 (6.41)	5.45 (4.05)	9.79 (8.03)	10.46 (4.9)
psoas	9.74 (6.6)	10.25 (6.39)	6.14 (3.88)	11.82 (10.24)	11.29 (5.3)
quad fem	3.06 (1.51)	3.16 (2.48)	2.59 (1.5)	3.41 (3.22)	3.91 (3.08)
gem	1.12 (2.4)	1.12 (2.05)	0.59 (0.8)	1.01 (1.11)	1.34 (1.35)
peri	2.87 (2.19)	2.02 (2.15)	1.49 (1.8)	1.36 (1.96)	2.54 (2.42)
rect fem	13.58 (5.58)	14.02 (7.61)	12.81 (4.63)	17.24 (12.09)	11.31 (8.49)
vas med	3.3 (1.97)	2.31 (2.89)	1.28 (0.78)	3.55 (5.08)	1.84 (2.01)
vas int	4.27 (2.2)	2.81 (3.33)	1.57 (0.95)	4.35 (6.28)	2.09 (2.33)
vas lat	6.46 (3.56)	4.49 (5.39)	2.39 (1.82)	7.3 (10.86)	3.48 (4.14)
med gas	8.98 (4.78)	10.24 (5.39)	9.77 (5.01)	8.4 (6.77)	14.22 (5.29)
lat gas	5.18 (3.4)	4.4 (3.57)	3.05 (2.66)	1.75 (1.61)	7.65 (2.34)
soleus	18.67 (14)	19.18 (14.46)	12.96 (7.86)	10.69 (8.7)	33.75 (10.37)
tib post	17.74 (7.91)	14.61 (11.42)	10.84 (7.72)	14.97 (13.55)	22.85 (9.01)
flex dig	2.63 (1.29)	2.22 (1.86)	1.28 (0.93)	2.91 (2.26)	3.55 (1.44)
flex hal	2.98 (1.47)	2.39 (2.03)	1.19 (1.35)	2.19 (2.79)	3.97 (1.44)
tib ant	11.9 (3.68)	10.67 (5.62)	7.16 (4.18)	12.72 (8.34)	12.71 (4.98)
per brev	6.11 (2.78)	5.93 (3.28)	5.3 (1.89)	3.71 (2.42)	4.75 (4.24)
per long	11.51 (4.7)	11.36 (6.03)	10.9 (2.6)	8.16 (4.6)	9.68 (7.89)
per tert	2.77 (1.09)	2.49 (1.32)	2.85 (1)	2.34 (1.15)	1.83 (1.53)
ext dig	7.77 (2.17)	7.05 (2.42)	7.7 (1.4)	7.34 (1.55)	5.88 (3.22)
ext hal	2.26 (0.66)	1.94 (1.04)	1.55 (0.87)	2.55 (1.31)	1.89 (1.51)
ercspn	11.05 (6.2)	10.2 (8.92)	9.61 (9.08)	8.74 (8.46)	15.61 (13.33)
intobl	4.5 (1.87)	4.48 (3.77)	3.74 (2.73)	4 (4.85)	5.67 (4.31)
extobl	5.03 (2.61)	3.25 (2.99)	2.2 (2.21)	1.37 (0.52)	3.18 (2.05)

Table 5: The average and standard deviation of the maximum muscle force values of similarity-based groups during stance.

Table 6: The p-values of the comparison of the maximum muscle force values among similarity-based groups during stance.

	Healthy vs Group A	Healthy vs Group B	Healthy vs Group C	Healthy vs Group D	Group A vs Group B	Group A vs Group C	Group A vs Group D	Group B vs Group C	Group B vs Group D	Group C vs Group D
glut med	0.00	0.01	0.38	0.26	0.55	0.97	1.00	1.00	0.83	0.99
glut min	0.01	0.00	0.17	0.64	0.33	0.76	1.00	1.00	0.45	0.73
semimem	0.11	0.27	0.23	0.00	0.94	0.68	0.00	0.94	0.00	0.00
semiten	0.99	0.33	0.71	0.00	0.42	0.77	0.00	1.00	0.00	0.02
bifemlh	0.89	0.63	0.16	0.00	0.88	0.27	0.00	0.71	0.00	0.00
bifemsh	0.88	0.39	0.68	0.71	0.68	0.84	0.37	1.00	0.13	0.33
sar	0.20	0.11	0.99	0.92	0.65	1.00	1.00	0.91	0.73	1.00
add long	0.98	0.79	0.96	0.06	0.58	0.90	0.11	1.00	0.03	0.23
add brev	1.00	0.78	0.60	0.06	0.65	0.52	0.08	0.97	0.03	0.05
add mag	1.00	0.56	0.64	0.07	0.43	0.57	0.08	0.99	0.01	0.06
tfl	0.00	0.01	0.82	0.07	0.52	1.00	0.93	0.91	0.98	0.99
pect	0.83	0.85	0.54	0.27	0.50	0.75	0.57	0.31	0.14	1.00
grac	0.99	0.74	0.81	0.01	0.56	0.72	0.02	1.00	0.01	0.05
glut max	0.30	0.10	0.12	0.94	0.55	0.38	0.37	0.94	0.09	0.08
iliacus	0.76	0.41	1.00	1.00	0.77	1.00	1.00	0.96	0.81	1.00
psoas	0.99	0.38	0.97	0.94	0.22	0.99	0.98	0.53	0.28	1.00
quad fem	1.00	0.96	1.00	0.73	0.91	1.00	0.80	0.97	0.58	0.99
gem	1.00	0.93	1.00	1.00	0.92	1.00	1.00	1.00	0.90	1.00
peri	0.11	0.25	0.66	0.99	0.93	0.98	0.93	1.00	0.75	0.88
rect fem	1.00	1.00	0.85	0.84	0.98	0.90	0.71	0.81	0.98	0.58

Table 6

vas med	0.11	0.08	1.00	0.35	0.67	0.87	0.97	0.52	0.98	0.77
vas int	0.02	0.03	1.00	0.12	0.63	0.84	0.93	0.46	0.99	0.66
vas lat	0.08	0.05	1.00	0.27	0.60	0.78	0.96	0.38	0.98	0.63
med gas	0.57	0.99	1.00	0.01	1.00	0.96	0.09	0.99	0.22	0.29
lat gas	0.62	0.27	0.28	0.14	0.69	0.54	0.01	0.96	0.01	0.02
soleus	1.00	0.68	0.79	0.00	0.57	0.74	0.00	1.00	0.00	0.03
tib post	0.32	0.19	0.98	0.49	0.74	1.00	0.06	0.95	0.03	0.65
flex dig	0.53	0.06	1.00	0.38	0.32	0.92	0.06	0.41	0.01	0.96
flex hal	0.26	0.01	0.91	0.41	0.19	1.00	0.03	0.87	0.00	0.43
tib ant	0.55	0.02	1.00	0.99	0.15	0.93	0.67	0.30	0.05	1.00
per brev	1.00	0.92	0.56	0.63	0.96	0.63	0.73	0.90	0.99	0.98
per long	1.00	1.00	0.77	0.84	1.00	0.79	0.86	0.91	0.98	0.99
per tert	0.63	1.00	0.96	0.11	0.88	1.00	0.41	0.95	0.26	0.95
ext dig	0.32	1.00	1.00	0.08	0.89	1.00	0.47	1.00	0.31	0.81
ext hal	0.25	0.13	0.98	0.74	0.68	0.73	1.00	0.38	0.91	0.76
ercspn	0.97	0.98	0.98	0.43	1.00	1.00	0.23	1.00	0.41	0.62
intobl	1.00	0.95	1.00	0.79	0.95	1.00	0.76	1.00	0.59	0.9
extobl	0.00	0.01	0.07	0.20	0.72	0.66	1.00	0.99	0.91	0.78

Table 7: The average and standard deviation of the maximum muscle force values of each spatial component-based group.

	Healthy gait					Affected-limb gait				
	Gaussian 1	Gaussian 2	Gaussian 3	Gaussian 4	Gaussian 5	Gaussian 1	Gaussian 2	Gaussian 3	Gaussian 4	Gaussian 5
	Mean (std)	Mean (std)	Mean (std)	Mean (std)	Mean (std)	Mean (std)	Mean (std)	Mean (std)	Mean (std)	Mean (std)
glut med	16.68 (4.68)	11.04 (2.72)	12.54 (4.11)	10.83 (2.65)	12.45 (5.35)	9.2 (5.36)	9.2 (6.55)	8.03 (3.37)	8.22 (2.32)	10.22 (5.6)
glut min	6.64 (2.66)	4.8 (1.82)	4.44 (2.22)	3.5 (1.43)	5.99 (3.24)	3.8 (2.53)	3.39 (3.38)	2.27 (1.53)	2.89 (1.54)	3.74 (2.58)
semimem	5.61 (3.22)	4.69 (1.99)	4.7 (2.17)	4.11 (2.04)	5.34 (3.49)	6.26 (3.96)	4.86 (3.95)	2.51 (2.68)	5.28 (4.93)	3.25 (2.75)
semiten	1.91 (1.3)	1.19 (1.09)	1.64 (1.18)	1.15 (0.63)	2.46 (2.01)	2.53 (1.99)	2.01 (2.05)	0.49 (0.47)	2.55 (2.6)	1.38 (1.3)
bifemlh	4.22 (1.62)	3.78 (1.36)	4.21 (2.11)	3.49 (1.14)	5.03 (2.53)	5.7 (3.55)	3.61 (3.87)	2.72 (2.34)	5.18 (4.84)	3.35 (2.95)
bifemsh	8.99 (2.54)	6.68 (1.35)	6.83 (2.22)	6.02 (2.49)	8.81 (3.76)	8.28 (2.83)	6.95 (4.12)	5.26 (2.01)	7 (3.99)	6.72 (3.24)
sar	2.13 (0.61)	1.97 (0.59)	1.78 (0.73)	1.59 (0.9)	2.16 (0.97)	1.77 (0.96)	1.46 (1.13)	1.1 (0.52)	1.18 (0.53)	1.65 (0.86)
add long	3.86 (3.22)	1.93 (1.69)	2.88 (2.56)	2.63 (2.09)	4.78 (2.75)	5.09 (3.47)	5.36 (4.3)	1.11 (1.99)	4.16 (4.45)	3.05 (3.09)
add brev	2.82 (2.33)	1.68 (1)	2.07 (1.91)	1.48 (1.22)	3.47 (2.58)	3.83 (3.1)	3.71 (3.65)	0.65 (1.06)	2.64 (3.46)	2.06 (2.62)
add mag	3.47 (2.26)	2.26 (1.1)	2.54 (2.01)	1.78 (0.93)	3.78 (2.45)	4.56 (3.7)	3.79 (4.07)	0.78 (0.99)	3.6 (4.68)	2.39 (2.99)
tfl	3.5 (1.21)	3.11 (1.12)	2.52 (1.06)	2.25 (0.9)	3.15 (1.67)	1.93 (1.12)	1.87 (1.23)	1.61 (0.8)	1.75 (0.67)	2.39 (1.09)
pect	1.4 (1.13)	0.86 (0.57)	0.94 (1)	0.85 (0.95)	1.48 (1.28)	2.21 (1.69)	1.73 (1.78)	0.26 (0.21)	1.55 (2.13)	1.08 (1.41)
grac	0.63 (0.64)	0.38 (0.54)	0.49 (0.56)	0.34 (0.44)	0.97 (0.81)	1.01 (0.92)	0.85 (1.02)	0.13 (0.16)	0.95 (1.2)	0.5 (0.67)
glut max	6.02 (3.82)	5.61 (1.91)	6.81 (3.03)	5.25 (2.55)	5.96 (3.44)	5.26 (4.94)	4.55 (5.23)	2.81 (2.71)	3.61 (2.61)	5.01 (4.75)
iliacus	9.43 (7.36)	4.57 (1.66)	13.63 (20.24)	20.86 (36.97)	10.02 (5.73)	11.06 (5.3)	8.8 (5.81)	4.11 (2.26)	11.39 (6.84)	8.82 (6.63)
psoas	8.03 (3.53)	7.03 (2.1)	9.91 (7.1)	11.24 (12.12)	12.18 (6.13)	12.16 (5.69)	9.05 (5.33)	4.94 (2.61)	12.11 (7.06)	9.55 (6.59)
quad fem	3.11 (2.02)	2.41 (0.56)	2.85 (1.18)	2.5 (1.09)	4.13 (1.75)	3.97 (2.78)	3.38 (3.15)	2.14 (1.29)	1.81 (0.76)	3.05 (2.4)
gem	2.43 (5.31)	0.72 (0.41)	0.86 (0.58)	0.48 (0.32)	0.91 (0.76)	1.13 (1.19)	1.02 (1.06)	0.41 (0.78)	0.19 (0.12)	1.26 (2.35)
peri	2.8 (2.51)	2.45 (0.47)	3.31 (2.29)	2.4 (1.91)	2.59 (2.62)	2.09 (2.19)	2.36 (2)	1.05 (1.67)	0.57 (0.56)	2.19 (2.22)

Table 7

rect fem	13.79 (4.07)	13.56 (4.06)	12.72 (5.46)	11.2 (4.68)	16.32 (7.79)	14.22 (8.28)	11.91 (8.48)	12.29 (4.22)	10.34 (5.59)	14.19 (7.77)
vas med	2.55 (1.55)	3.28 (1.53)	3.39 (1.71)	2.58 (0.99)	4.25 (3.02)	2.06 (1.96)	1.43 (1.02)	0.99 (0.46)	1.6 (1.51)	2.59 (3.39)
vas int	3.41 (1.79)	4.04 (1.78)	4.42 (1.99)	3.55 (1.45)	5.34 (3.14)	2.42 (2.33)	1.68 (1.2)	1.24 (0.65)	2 (1.91)	3.16 (3.91)
vas lat	5.07 (3.46)	6.17 (2.13)	6.7 (2.96)	5.36 (2)	8.12 (5.41)	3.94 (4.14)	2.78 (2.34)	1.72 (1.03)	3.07 (3.37)	5.08 (6.29)
med gas	10.07 (3.57)	8.58 (4.27)	9.09 (5.39)	6.35 (3.83)	9.24 (5.47)	11.33 (5.28)	12.89 (4.62)	9.03 (4.69)	13.64 (7.06)	9.84 (5.51)
lat gas	6.3 (3.91)	5.09 (3.45)	4.22 (2.98)	4.85 (4.17)	6.2 (3.22)	5.79 (3.54)	5.59 (4.05)	2.38 (2.05)	5.2 (4)	3.99 (3.43)
soleus	23.98 (17.16)	13.66 (10.98)	18.45 (13.66)	14.41 (11.81)	19.24 (14.26)	26.26 (16.24)	22.8 (11)	12.28 (7.5)	18.62 (8.02)	17.31 (13.69)
tib post	19.81 (7.89)	15.92 (8.11)	15.57 (7.59)	15.89 (10.12)	22.12 (5.95)	20.61 (10.52)	17.98 (10.75)	8.85 (7.89)	13.92 (8.19)	12.99 (11.29)
flex dig	3.14 (1.53)	2.88 (1.07)	2.18 (1.24)	2.46 (1.3)	2.94 (1.14)	2.98 (1.71)	2.4 (1.97)	1.21 (0.9)	2.21 (1.22)	2.08 (1.92)
flex hal	3.85 (1.27)	3.34 (1.52)	2.36 (1.48)	2.63 (1.64)	3.31 (1.09)	3.19 (2.01)	2.52 (2.36)	1.02 (1.23)	2.4 (1.79)	2.23 (2.01)
tib ant	13.78 (2.34)	9.17 (2.34)	10.62 (3.15)	9.35 (2.47)	15.67 (3.29)	11.48 (6.19)	9.13 (4.77)	7.13 (4.39)	12.78 (4.94)	10.59 (5.5)
per brev	6.91 (2.3)	5.06 (2.18)	5.94 (2.34)	4.73 (2.54)	7.07 (4.09)	5.66 (3.52)	5.1 (3.47)	5.25 (2.25)	4.53 (3.01)	5.92 (3.31)
per long	12.06 (3.97)	10.53 (3.05)	11.32 (4.09)	9.37 (4.92)	13.05 (6.97)	10.77 (6.53)	10.44 (6.46)	11.2 (2.87)	8 (5.07)	11.49 (6.04)
per tert	3 (0.93)	2.61 (0.76)	2.62 (0.99)	2.57 (0.86)	3.07 (1.66)	2.19 (1.27)	2.17 (1.36)	3.03 (0.97)	1.71 (1.25)	2.59 (1.36)
ext dig	8.45 (1.75)	7.08 (1.23)	7.14 (1.84)	6.47 (1.22)	9.46 (2.93)	6.68 (2.27)	6.74 (2.9)	7.87 (1.32)	5.44 (2.38)	7.21 (2.56)
ext hal	2.61 (0.44)	1.96 (0.24)	1.98 (0.49)	1.61 (0.51)	3 (0.59)	2.04 (1.2)	1.52 (1.25)	1.66 (0.89)	2.03 (0.99)	1.92 (1.07)
ercspn	12.67 (6.52)	7.8 (2.64)	11.04 (6.47)	9.94 (6.58)	12.17 (6.81)	14.1 (11.05)	14.11 (11.9)	6.29 (3.54)	4.58 (2.4)	9.73 (8.77)
intobl	5.77 (1.99)	2.75 (0.82)	4.27 (1.55)	3.72 (1.53)	5.27 (1.94)	5.38 (3.44)	4.79 (3.54)	3.03 (1.97)	2.38 (1.97)	4.46 (4.15)
extobl	7.5 (3.16)	2.98 (1.24)	4.49 (2.15)	4 (2.4)	5.55 (1.78)	3.9 (2.69)	4.29 (2.8)	1.39 (0.78)	1.55 (0.58)	2.95 (3.04)

Table 8: The p-values of the muscles that showed significant difference (p-value ≤ 0.05) in at least one comparison of the maximum muscle force values among spatial component-based groups during stance. HG stands for Gaussians of healthy gait and AG stands for Gaussians of the gait of hip OA patients.

	HG 1 vs HG 2	HG 1 vs HG 3	HG 1 vs HG 4	HG 1 vs HG 5	HG 1 vs AG 1	HG 1 vs AG 2	HG 1 vs AG 3	HG 1 vs AG 4	HG 1 vs AG 5	HG 2 vs HG 3	HG 2 vs HG 4	HG 2 vs HG 5
glut med	0.29	0.36	0.36	0.55	0.00	0.08	0.00	0.03	0.00	1.00	1.00	1.00
glut min	0.84	0.26	0.25	1.00	0.02	0.21	0.00	0.08	0.01	1.00	0.99	0.99
semimem	1.00	1.00	0.99	1.00	1.00	1.00	0.37	1.00	0.32	1.00	1.00	1.00
semiten	0.99	1.00	0.99	1.00	0.97	1.00	0.47	1.00	0.98	1.00	1.00	0.72
bifemlh	1.00	1.00	1.00	1.00	0.88	1.00	0.97	1.00	0.99	1.00	1.00	0.99
add long	0.93	1.00	1.00	1.00	0.97	0.99	0.53	1.00	1.00	1.00	1.00	0.57
add brev	0.99	1.00	0.99	1.00	0.97	1.00	0.61	1.00	0.99	1.00	1.00	0.88
add mag	1.00	1.00	0.98	1.00	0.98	1.00	0.48	1.00	0.98	1.00	1.00	0.98
tfl	1.00	0.28	0.44	1.00	0.00	0.10	0.00	0.06	0.05	0.95	0.92	1.00
pect	1.00	0.99	1.00	1.00	0.76	1.00	0.63	1.00	1.00	1.00	1.00	0.99
grac	1.00	1.00	1.00	0.98	0.85	1.00	0.85	1.00	1.00	1.00	1.00	0.75
psoas	1.00	1.00	0.99	0.84	0.62	1.00	0.98	0.95	1.00	0.98	0.97	0.73
vas int	1.00	0.99	1.00	0.83	0.99	0.97	0.77	0.99	1.00	1.00	1.00	0.99
vas lat	1.00	0.99	1.00	0.86	1.00	0.99	0.83	1.00	1.00	1.00	1.00	1.00
tib post	1.00	0.97	1.00	1.00	1.00	1.00	0.21	0.97	0.45	1.00	1.00	0.93
flex hal	1.00	0.37	0.94	1.00	0.99	0.90	0.01	0.85	0.12	0.95	1.00	1.00
tib ant	0.54	0.71	0.72	0.99	0.92	0.66	0.05	1.00	0.54	1.00	1.00	0.10
ext dig	0.95	0.84	0.77	0.99	0.38	0.89	1.00	0.20	0.78	1.00	1.00	0.40
ext hal	0.89	0.69	0.51	0.99	0.73	0.38	0.35	0.97	0.37	1.00	1.00	0.32

Table 8

extobl	0.01	0.04	0.18	0.71	0.00	0.29	0.00	0.00	0.00	0.92	1.00	0.48
	HG 2 vs AG 1	HG 2 vs AG 2	HG 2 vs AG 3	HG 2 vs AG 4	HG 2 vs AG 5	HG 3 vs HG 4	HG 3 vs HG 5	HG 3 vs AG 1	HG 3 vs AG 2	HG 3 vs AG 3	HG 3 vs AG 4	HG 3 vs AG 5
glut med	1.00	1.00	0.96	0.99	1.00	1.00	1.00	0.27	0.91	0.33	0.68	0.64
glut min	0.99	0.99	0.50	0.92	0.98	1.00	0.76	0.99	1.00	0.38	0.94	0.97
semimem	0.96	1.00	0.90	1.00	0.97	1.00	1.00	0.68	1.00	0.69	1.00	0.63
semiten	0.43	0.99	0.99	0.82	1.00	1.00	0.88	0.46	1.00	0.60	0.95	1.00
bifemlh	0.80	1.00	1.00	1.00	1.00	1.00	1.00	0.64	1.00	0.93	1.00	0.96
add long	0.21	0.55	1.00	0.94	0.99	1.00	0.76	0.17	0.75	0.88	1.00	1.00
add brev	0.49	0.90	1.00	1.00	1.00	1.00	0.87	0.22	0.93	0.90	1.00	1.00
add mag	0.58	0.99	0.99	1.00	1.00	1.00	0.97	0.21	0.99	0.84	1.00	1.00
tfl	0.18	0.56	0.13	0.43	0.79	1.00	0.85	0.63	0.96	0.50	0.90	1.00
pect	0.26	0.97	1.00	1.00	1.00	1.00	0.98	0.02	0.96	0.95	0.99	1.00
grac	0.43	0.97	1.00	0.91	1.00	1.00	0.70	0.17	0.99	0.95	0.93	1.00
psoas	0.54	1.00	1.00	0.89	0.99	1.00	0.99	0.94	1.00	0.52	1.00	1.00
vas int	0.92	0.89	0.57	0.95	1.00	1.00	1.00	0.22	0.55	0.10	0.72	0.72
vas lat	0.97	0.95	0.62	0.97	1.00	1.00	1.00	0.48	0.73	0.14	0.81	0.92
tib post	0.97	1.00	0.89	1.00	1.00	1.00	0.68	0.65	1.00	0.72	1.00	0.98
flex hal	1.00	1.00	0.17	0.99	0.83	1.00	0.90	0.78	1.00	0.61	1.00	1.00
tib ant	0.97	1.00	1.00	0.94	1.00	1.00	0.10	1.00	1.00	0.67	0.99	1.00
ext dig	1.00	1.00	1.00	0.95	1.00	1.00	0.11	1.00	1.00	1.00	0.83	1.00
ext hal	1.00	1.00	1.00	1.00	1.00	1.00	0.07	1.00	0.99	1.00	1.00	1.00

Table 8

extobl	1.00	1.00	0.96	0.99	1.00	1.00	0.98	1.00	1.00	0.05	0.28	0.27
	HG 4 vs HG 5	HG 4 vs AG 1	HG 4 vs AG 2	HG 4 vs AG 3	HG 4 vs AG 4	HG 4 vs AG 5	HG 5 vs AG 1	HG 5 vs AG 2	HG 5 vs AG 3	HG 5 vs AG 4	HG 5 vs AG 5	AG 1 vs AG 2
glut med	1.00	1.00	1.00	0.99	1.00	1.00	0.65	0.95	0.56	0.80	0.92	1.00
glut min	0.60	1.00	1.00	0.99	1.00	1.00	0.21	0.53	0.02	0.27	0.11	1.00
semimem	1.00	0.86	1.00	0.99	1.00	1.00	1.00	1.00	0.51	1.00	0.50	0.99
semiten	0.78	0.56	0.99	1.00	0.85	1.00	1.00	1.00	0.08	1.00	0.41	1.00
bifemlh	0.99	0.78	1.00	1.00	0.99	1.00	1.00	0.99	0.69	1.00	0.70	0.83
add long	0.92	0.72	0.87	0.99	1.00	1.00	1.00	1.00	0.14	1.00	0.73	1.00
add brev	0.87	0.54	0.89	1.00	1.00	1.00	1.00	1.00	0.22	1.00	0.76	1.00
add mag	0.93	0.48	0.97	1.00	0.99	1.00	1.00	1.00	0.31	1.00	0.88	1.00
tfl	0.84	1.00	1.00	0.99	1.00	1.00	0.04	0.40	0.04	0.27	0.49	1.00
pect	1.00	0.43	0.98	1.00	1.00	1.00	0.85	1.00	0.54	1.00	1.00	1.00
grac	0.78	0.54	0.97	1.00	0.91	1.00	1.00	1.00	0.17	1.00	0.57	1.00
psoas	1.00	1.00	1.00	0.63	1.00	1.00	1.00	0.99	0.17	1.00	0.95	0.98
vas int	0.97	1.00	0.98	0.88	1.00	1.00	0.08	0.26	0.03	0.39	0.33	1.00
vas lat	0.98	1.00	1.00	0.9	1.00	1.00	0.21	0.43	0.05	0.51	0.57	1.00
tib post	0.96	0.99	1.00	0.93	1.00	1.00	1.00	1.00	0.05	0.81	0.09	1.00
flex hal	1.00	1.00	1.00	0.78	1.00	1.00	1.00	1.00	0.09	0.99	0.67	1.00
tib ant	0.22	0.99	1.00	1.00	0.97	1.00	0.23	0.18	0.00	0.97	0.03	0.99
ext dig	0.21	1.00	1.00	0.97	1.00	1.00	0.01	0.33	0.83	0.02	0.05	1.00
ext hal	0.09	0.99	1.00	1.00	1.00	1.00	0.07	0.05	0.03	0.56	0.01	0.97

Table 8

extobl	0.97	1.00	1.00	0.63	0.83	0.99	0.68	0.99	0.01	0.07	0.05	1.00

	AG 1 vs AG 3	AG 1 vs AG 4	AG 1 vs AG 5	AG 2 vs AG 3	AG 2 vs AG 4	AG 2 vs AG 5	AG 3 vs AG 4	AG 3 vs AG 5	AG 4 vs AG 5
glut med	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.96	1.00
glut min	0.79	1.00	1.00	1.00	1.00	1.00	1.00	0.77	1.00
semimem	0.03	1.00	0.00	0.91	1.00	0.97	0.78	1.00	0.88
semiten	0.01	1.00	0.01	0.65	1.00	0.99	0.21	0.79	0.73
bifemlh	0.11	1.00	0.00	1.00	1.00	1.00	0.82	1.00	0.90
add long	0.01	1.00	0.05	0.18	1.00	0.76	0.65	0.69	1.00
add brev	0.02	0.99	0.03	0.37	1.00	0.89	0.89	0.83	1.00
add mag	0.01	1.00	0.01	0.59	1.00	0.98	0.68	0.83	0.99
tfl	1.00	1.00	0.64	1.00	1.00	0.99	1.00	0.57	0.95
pect	0.00	0.99	0.00	0.53	1.00	0.98	0.71	0.76	1.00
grac	0.02	1.00	0.03	0.64	1.00	0.98	0.46	0.88	0.91
psoas	0.04	1.00	0.62	0.96	1.00	1.00	0.44	0.48	0.99
vas int	0.98	1.00	0.97	1.00	1.00	0.97	1.00	0.63	1.00
vas lat	0.95	1.00	0.98	1.00	1.00	0.98	1.00	0.54	0.99
tib post	0.03	0.88	0.01	0.74	1.00	0.97	0.99	0.97	1.00
flex hal	0.03	0.99	0.25	0.84	1.00	1.00	0.90	0.61	1.00
tib ant	0.28	1.00	1.00	1.00	0.95	1.00	0.42	0.53	0.99
ext dig	0.91	0.97	0.98	0.99	0.99	1.00	0.55	1.00	0.72
ext hal	0.98	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00
extobl	0.18	0.57	0.77	0.48	0.72	0.97	1.00	0.75	0.96

Table 9: The average and standard deviation of the maximum muscle force values of similarity-based groups for each stance phase.

	Heel contact						Foot flat				
	Healthy	Group A	Group B	Group C	Group D		Healthy	Group A	Group B	Group C	Group D
glut med	3.16 (3.35)	5.89 (4.3)	4.58 (2.23)	9.07 (4.36)	1.58 (1.32)	glut med	7.05 (4.72)	9.84 (4.7)	11.66 (3.15)	12.69 (2.78)	7.08 (3.61)
glut min	1.06 (1.75)	2.12 (2.3)	1.25 (1.08)	3.34 (2.75)	0.44 (0.3)	glut min	2.47 (2.36)	3.69 (2.67)	5.11 (2.43)	5.06 (2.34)	2.43 (1.88)
semimem	1.89 (2.52)	4.05 (2.73)	1.95 (1.59)	5.66 (3.36)	2.76 (1.46)	semimem	2.82 (2.8)	5.5 (3.55)	3.55 (2.91)	6.07 (4.71)	5.64 (3.29)
semiten	0.47 (0.59)	1.01 (1)	0.53 (0.26)	0.75 (0.97)	0.53 (0.39)	semiten	0.99 (1.01)	1.71 (1.68)	1.05 (1.13)	2.02 (2.6)	1.87 (1.72)
bifemlh	1.41 (1.67)	3.64 (2.49)	2.71 (2.65)	4.72 (3.69)	1.99 (1.58)	bifemlh	2.42 (2.06)	4.88 (3.14)	4.7 (2.94)	4.86 (4.29)	4.93 (3.19)
bifemsh	2.5 (1.9)	4.61 (3.79)	4.39 (3.07)	3.81 (2.35)	1.71 (2.69)	bifemsh	4.45 (2.63)	6.18 (3.65)	6.3 (3.32)	7.01 (5.26)	5.43 (4.24)
sar	0.52 (0.5)	1.11 (0.9)	1.55 (0.84)	1.46 (0.53)	0.3 (0.52)	sar	1.02 (0.68)	1.57 (0.88)	2.1 (0.74)	2 (1.12)	1.32 (1.02)
add long	0.64 (1.1)	1.68 (1.96)	0.37 (0.38)	1.85 (2.44)	0.54 (0.38)	add long	1.35 (1.62)	2.45 (2.27)	0.81 (1.43)	4.8 (5.49)	3.22 (2.19)
add brev	0.5 (1.05)	1.3 (1.53)	0.25 (0.23)	1.36 (2.42)	0.42 (0.31)	add brev	1.08 (1.48)	1.85 (1.99)	0.52 (0.86)	3.43 (4.05)	2.66 (2.52)
add mag	0.63 (0.99)	1.53 (1.35)	0.95 (0.45)	1.19 (2.06)	0.73 (0.61)	add mag	1.19 (1.4)	2.32 (2.1)	1.3 (0.9)	3.49 (4.21)	3.13 (2.78)
tfl	0.68 (0.65)	1.22 (1.13)	0.66 (0.6)	1.52 (0.78)	0.3 (0.4)	tfl	1.42 (1.02)	2.17 (1.35)	2.84 (1.5)	2.42 (0.82)	1.48 (0.96)
pect	0.23 (0.51)	0.62 (0.77)	0.31 (0.34)	0.74 (0.84)	0.16 (0.24)	pect	0.43 (0.72)	0.9 (1.09)	0.32 (0.32)	1.76 (1.98)	0.94 (1.3)
grac	0.11 (0.2)	0.32 (0.47)	0.06 (0.02)	0.36 (0.63)	0.12 (0.15)	grac	0.27 (0.41)	0.57 (0.76)	0.11 (0.12)	0.92 (1.19)	0.77 (0.84)
glut max	1.59 (1.94)	3.12 (3.16)	1.68 (2.15)	4.14 (3.54)	1.27 (0.98)	glut max	3.01 (3.27)	5.85 (3.45)	6.59 (3.56)	7.4 (3.62)	5.17 (3.84)
iliacus	2.58 (2.24)	4.31 (4.95)	0.9 (1.27)	6.43 (6.65)	0.85 (1.02)	iliacus	4.84 (3.75)	6.4 (8.97)	1.8 (1.69)	10.45 (8.58)	9.28 (13.07)
psoas	3.02 (2.39)	4.62 (4.45)	1 (1.53)	6.5 (6.42)	1.16 (1.49)	psoas	5.53 (3.51)	6.85 (5.87)	3.72 (4.46)	10.63 (7.84)	6.5 (6.51)
quad fem	0.78 (0.9)	1.96 (2.3)	1.58 (0.78)	1.9 (1.88)	0.84 (0.62)	quad fem	1.43 (1.04)	2.37 (2.13)	2.35 (0.83)	2.32 (1.86)	2.54 (2.39)
gem	0.47 (2.42)	0.76 (3.08)	0.04 (0.07)	0.65 (0.76)	0.08 (0.07)	gem	0.72 (2.34)	0.89 (3.09)	0.11 (0.24)	0.58 (0.74)	0.73 (1)
peri	0.63 (1.09)	1.38 (1.39)	1.2 (1.04)	1.93 (1.98)	0.49 (0.6)	peri	1.62 (1.98)	2.04 (1.6)	2.17 (1.15)	1.94 (2.15)	2.2 (2.18)
rect fem	3.04 (3.05)	6.91 (5.34)	6.46 (4.17)	9.4 (5.68)	1.52 (1.02)	rect fem	7.55 (4.66)	10.64 (5.63)	12.63 (6.02)	14.15 (3.57)	7.63 (6)

Table 9

vas med	0.97 (0.85)	1.23 (0.96)	1.01 (0.76)	2.63 (3.66)	0.55 (0.23)	vas med	2.02 (1.85)	2.22 (1.67)	2.25 (2.34)	6.12 (7.32)	1.23 (1.07)
vas int	1.15 (1.07)	1.6 (1.29)	1.29 (0.98)	2.97 (3.77)	0.64 (0.29)	vas int	2.48 (2.04)	2.89 (2.12)	2.81 (2.63)	7.03 (7.28)	1.46 (1.31)
vas lat	1.77 (1.91)	2.38 (2.17)	1.97 (1.8)	3.91 (4.76)	0.96 (0.52)	vas lat	3.72 (3.46)	4.44 (3.17)	4.09 (3.52)	9.46 (8.87)	2.44 (2.39)
med gas	1.53 (1.41)	3.81 (3.62)	4.45 (3.43)	4.55 (4.54)	1.17 (0.62)	med gas	4.04 (2.76)	7.48 (4.78)	6.8 (3.55)	11.04 (9.55)	6.8 (6.35)
lat gas	0.82 (1.14)	2.59 (2.51)	2.59 (1.54)	1.53 (1.57)	0.65 (0.94)	lat gas	1.73 (1.76)	3.95 (3.06)	3.18 (2.07)	4.64 (3.66)	4.95 (3.64)
soleus	2.17 (2)	9.77 (10.06)	5.31 (9.11)	5.77 (8.63)	2.49 (3.26)	soleus	6.69 (6.31)	13.11 (9.39)	8.65 (8.69)	15.63 (16.27)	12.68 (7.89)
tib post	5.77 (4.3)	10.8 (7.56)	9.21 (6.45)	14.24 (8.36)	3.68 (2.47)	tib post	9.22 (3.68)	13.23 (6.67)	11.93 (5.63)	17.68 (10.2)	13.52 (5.68)
flex dig	0.78 (0.93)	1.47 (1.28)	1.45 (1.09)	1.58 (1.42)	0.3 (0.21)	flex dig	1.19 (1)	1.88 (1.18)	1.63 (0.93)	3.49 (3.26)	1.84 (0.97)
flex hal	0.79 (1.09)	1.5 (1.4)	1.58 (1.06)	1.62 (1.44)	0.31 (0.31)	flex hal	1.29 (1.2)	1.97 (1.34)	1.73 (0.96)	3.67 (2.83)	2.12 (1.23)
tib ant	5.73 (3.7)	9.07 (4.86)	10.25 (3.72)	8.85 (5.21)	4.53 (4.59)	tib ant	7.84 (4.04)	10.37 (4.42)	11.13 (3.59)	11.17 (3.72)	9.46 (5.72)
per brev	1.75 (1.09)	3.64 (2.7)	4.11 (2.13)	5.29 (3.6)	1.26 (1.75)	per brev	2.65 (1.65)	5.21 (2.89)	7.01 (2.24)	6.83 (2.41)	3.83 (2.46)
per long	4.01 (2.16)	6.51 (4.53)	7.26 (3.23)	9.91 (4.72)	2.68 (2.41)	per long	5.47 (2.71)	9.46 (4.83)	13.41 (4.8)	13.12 (3.53)	7.14 (3.46)
per tert	0.55 (0.6)	1.57 (1.28)	1.69 (1.2)	2.53 (1.49)	0.41 (0.5)	per tert	1.33 (1.01)	2.38 (1.33)	2.89 (1.02)	2.99 (1.09)	1.76 (1.28)
ext dig	3.26 (1.56)	4.64 (2.97)	5.28 (2.79)	7.89 (3.67)	2.13 (1.55)	ext dig	5.23 (1.94)	6.22 (2.43)	7.12 (1.55)	7.84 (2.78)	4.59 (2.96)
ext hal	0.61 (0.61)	1.49 (1.07)	1.68 (1.01)	1.83 (1.09)	0.66 (1.13)	ext hal	1.3 (0.84)	2 (0.95)	2.27 (0.56)	2.36 (0.88)	1.72 (1.17)
ercspn	3.21 (4.34)	5.23 (5.68)	3.92 (3.11)	6.82 (5.71)	2.23 (1.12)	ercspn	7.64 (5.54)	7.31 (5.84)	10.11 (6.62)	7.29 (3.94)	6.16 (3.13)
intobl	1.48 (1.71)	3.02 (3.15)	2.63 (2.45)	4.33 (4.37)	0.53 (0.23)	intobl	2.65 (1.64)	3.34 (2.83)	4.05 (3.85)	4.53 (3.4)	1.85 (1.05)
extobl	1.5 (1.53)	2.18 (2.23)	1.76 (2.44)	3.04 (2.38)	0.69 (0.19)	extobl	2.38 (2.13)	2.62 (2.2)	2.41 (3.24)	3.89 (1.85)	1.31 (0.64)
			Mid-stance						Heel off		
	Healthy	Group A	Group B	Group C	Group D		Healthy	Group A	Group B	Group C	Group D
glut med	7.55 (4.2)	11.53 (5.32)	13.03 (4.45)	10.09 (3.94)	13.95 (6.27)	glut med	5.19 (2.94)	12.01 (5.6)	15.58 (3.94)	8.88 (6.2)	10.73 (7.76)
glut min	2.66 (1.97)	4.27 (2.66)	5.9 (2.56)	3.99 (1.62)	5.71 (3.22)	glut min	1.7 (1.66)	4.73 (2.7)	6.86 (2.03)	4.03 (1.43)	4.48 (3.65)
semimem	2.5 (2.66)	4.92 (4.76)	2.88 (4.18)	3.08 (5.61)	9.9 (3.71)	semimem	1.95 (1.78)	4.15 (4.16)	3.2 (4.05)	0.63 (0.51)	9.14 (4.56)

Table 9

semiten	0.94 (1.09)	1.54 (1.97)	0.8 (1.4)	1.15 (1.99)	3.44 (1.85)	semiten	0.77 (1.09)	1.39 (1.82)	0.73 (1.37)	0.17 (0.1)	3.42 (1.97)
bifemlh	2.21 (1.89)	4.4 (4.16)	4.39 (4.17)	2.99 (4.68)	8.93 (3.54)	bifemlh	2.12 (1.54)	3.52 (3.79)	4.01 (4.02)	0.44 (0.28)	7.99 (3.9)
bifemsh	5.18 (3.13)	5.71 (4)	5.9 (3.99)	5.82 (6.39)	10.44 (1.84)	bifemsh	5 (3.64)	6.67 (3.93)	8.22 (3.11)	4.43 (4.18)	9.44 (3.61)
sar	1.3 (0.82)	1.69 (0.93)	2.24 (0.81)	1.94 (1.17)	2.4 (0.84)	sar	1.19 (0.97)	1.89 (0.88)	2.36 (0.57)	2.05 (1.28)	1.82 (1.3)
add long	1.52 (1.85)	2.29 (3.21)	1.1 (2.48)	1.88 (2.78)	6.4 (3.42)	add long	2.07 (2.26)	2.74 (3.62)	1.89 (2.99)	2.43 (4)	5.28 (3.17)
add brev	1.04 (1.33)	1.76 (2.65)	0.92 (2.2)	1 (1.46)	5.36 (2.98)	add brev	1.26 (1.27)	2.03 (2.84)	1.46 (2.44)	0.49 (0.62)	4.12 (2.83)
add mag	1.21 (1.3)	2.23 (3.03)	0.97 (1.9)	1.52 (2.55)	5.86 (3.43)	add mag	1.61 (1.27)	2.24 (3.08)	1.35 (2.11)	1 (1.53)	4.08 (2.9)
tfl	1.69 (1.24)	2.46 (1.32)	3.46 (1.39)	2.68 (1.11)	2.56 (1.47)	tfl	1.24 (0.94)	2.55 (1.3)	3.8 (1.09)	2.8 (0.85)	2.16 (1.81)
pect	0.51 (0.72)	0.8 (1.31)	0.38 (0.99)	1.75 (1.94)	2.48 (1.45)	pect	0.52 (0.66)	1.07 (1.54)	0.63 (1.12)	2.1 (2.39)	1.9 (1.57)
grac	0.26 (0.38)	0.6 (0.94)	0.15 (0.25)	0.27 (0.43)	1.62 (0.87)	grac	0.19 (0.32)	0.54 (0.81)	0.36 (0.63)	0.06 (0.02)	1.16 (0.91)
glut max	3.33 (3.05)	5.89 (4.02)	6.75 (3.69)	3.77 (1.9)	8.73 (5.44)	glut max	1.79 (1.66)	5.68 (4.16)	7.08 (3.53)	1.72 (2.36)	7.34 (5.24)
iliacus	4.81 (3.48)	6.31 (5.85)	2.77 (4.7)	6.99 (8.04)	11.44 (4.44)	iliacus	7.33 (17.9)	8.58 (7.21)	3.62 (5.7)	8.67 (8.4)	9.96 (6.39)
psoas	5.68 (3.82)	7.17 (6.24)	2.66 (4.37)	8.97 (9.65)	11.38 (3.93)	psoas	5.48 (7.44)	9.37 (7.36)	3.95 (5.66)	11.49 (10.7)	11.27 (5.38)
quad fem	1.63 (0.96)	1.85 (2.34)	2.05 (1.48)	1.14 (0.99)	5.21 (2.88)	quad fem	1.55 (1.33)	2.41 (2.18)	3.04 (1.55)	2.04 (2.06)	3.62 (1.64)
gem	0.41 (0.33)	0.84 (2.99)	0.25 (0.7)	0.41 (0.72)	2.05 (1.62)	gem	0.2 (0.26)	0.97 (2.37)	0.69 (0.84)	0.6 (1.14)	1.21 (1.27)
peri	1.98 (1.73)	1.96 (1.88)	1.8 (1.63)	1.19 (1.4)	3.82 (3.09)	peri	1.1 (1.18)	2.27 (2.17)	2.62 (1.95)	1.46 (1.77)	2.86 (3.08)
rect fem	8.52 (5.36)	11.9 (6.41)	14.29 (6.1)	14.87 (5.7)	12.96 (7.48)	rect fem	6.51 (5.3)	14.42 (7.45)	18.81 (4.44)	18.52 (9.44)	10.66 (8.4)
vas med	2.18 (1.5)	2.46 (2.24)	2.15 (1.81)	4.44 (5.52)	1.55 (1.56)	vas med	1.74 (1.68)	2.69 (2.65)	1.87 (1.62)	5.61 (8.37)	1.4 (1.36)
vas int	3.11 (1.71)	3.16 (2.82)	2.84 (2.43)	5.69 (7.18)	1.83 (1.87)	vas int	2.1 (1.94)	3.41 (3.35)	2.4 (2.21)	7.15 (10.58)	1.59 (1.58)
vas lat	3.99 (3.05)	4.94 (4.44)	4.3 (3.83)	8.5 (10.96)	3.25 (3.59)	vas lat	3.4 (3.45)	5.42 (5.45)	3.58 (3.3)	10.52 (15.28)	2.72 (2.94)
med gas	6.37 (5.01)	7.86 (6.34)	7.13 (5.98)	7.81 (6.21)	13.6 (7.58)	med gas	6.29 (5.48)	11.18 (7.12)	11.69 (6.91)	9.31 (8.79)	13.11 (8.03)
lat gas	3.29 (2.69)	4.38 (4.2)	1.77 (3.56)	2.4 (2.98)	9.88 (3.39)	lat gas	4.29 (3.67)	4.59 (4.09)	3.22 (3.41)	2.2 (2.94)	8.6 (2.68)
soleus	10.89 (8.82)	13.15 (12.44)	6.6 (7.49)	5.2 (3.13)	35.68 (11.7)	soleus	16.12 (15.37)	17.67 (15.21)	13.41 (10.29)	8.56 (8.09)	34.19 (11.62)

Table 9

tib post	12.4 (7.47)	12.67 (9.94)	7.39 (9.86)	14.66 (14.63)	26.02 (8.93)	tib post	14.42 (9.36)	12.71 (11.43)	9.34 (10.22)	13.89 (16.5)	21.87 (8.76)
flex dig	1.43 (1.03)	1.6 (1.4)	0.87 (1.5)	3.06 (3.25)	3.84 (1.4)	flex dig	1.73 (1.4)	1.78 (1.73)	1.09 (1.61)	2.62 (2.9)	3.48 (1.16)
flex hal	1.52 (1.31)	1.72 (1.58)	0.88 (1.66)	2.22 (3.55)	4.35 (1.54)	flex hal	1.97 (1.68)	1.9 (1.95)	1.14 (1.87)	1.65 (3.01)	3.91 (1.62)
tib ant	7.87 (3.64)	8.56 (4.2)	8.55 (4.67)	9.29 (4.56)	13.58 (3.5)	tib ant	8.58 (4.49)	8.63 (5.58)	8.5 (5.04)	11.65 (7.42)	10.98 (2.38)
per brev	3.21 (2.32)	6.01 (2.86)	7.64 (2.24)	5.09 (3.66)	6.93 (3.83)	per brev	3.21 (2.82)	6.25 (3.25)	8.07 (2.05)	4.52 (3.34)	5.05 (4.2)
per long	6.85 (4.03)	11.46 (5.12)	15.37 (4.8)	11.12 (7.04)	14.13 (7.47)	per long	6.09 (5.15)	11.92 (6.06)	16.47 (4.24)	9.46 (6.31)	10.21 (8.65)
per tert	1.51 (1.07)	2.36 (1.19)	2.96 (0.84)	2.03 (0.85)	2.66 (1.57)	per tert	1.15 (1.15)	2.25 (1.31)	3.34 (0.62)	1.92 (1.4)	1.84 (1.55)
ext dig	5.18 (2.29)	6.17 (2.55)	7.84 (1.39)	6.85 (0.68)	6.49 (3.65)	ext dig	4.13 (3.24)	5.87 (2.82)	8.25 (1.18)	6.13 (1.8)	4.71 (3.81)
ext hal	1.26 (0.8)	1.87 (0.81)	2.21 (0.58)	2.04 (0.83)	2.31 (0.66)	ext hal	1.29 (0.99)	1.82 (0.92)	2.28 (0.69)	2.39 (1.08)	1.9 (0.74)
ercspn	7.93 (5.15)	6.59 (5.28)	7.33 (7.6)	3.93 (1.87)	13.27 (7.4)	ercspn	4.74 (4.13)	7.77 (6.02)	7.77 (7.2)	6.14 (4.49)	13.08 (10.57)
intobl	3.29 (1.84)	3.57 (2.53)	3.18 (3.92)	1.73 (0.78)	5.26 (3.06)	intobl	3.39 (1.52)	4.25 (3.04)	3.27 (2.99)	3.1 (1.85)	5.3 (3.93)
extobl	3.66 (2.31)	2.82 (1.95)	2.26 (3.18)	1.95 (1.4)	2.94 (3.04)	extobl	4.01 (2.3)	3.36 (2.2)	2.32 (1.18)	1.93 (1)	2.86 (3.01)
						Toe off					
	Healthy	Group A	Group B	Group C	Group D		Healthy	Group A	Group B	Group C	Group D
glut med	9.42 (5.78)	9.91 (5.47)	7.55 (3.7)	8.29 (2.59)	9.74 (5.84)	rect fem	11.29 (6.25)	14.02 (7.61)	12.81 (4.63)	17.24 (12.09)	11.31 (8.49)
glut min	3.48 (2.76)	3.74 (2.56)	2.29 (1.68)	2.22 (1.46)	4.02 (2.71)	vas med	2.52 (1.69)	2.31 (2.89)	1.28 (0.78)	3.55 (5.08)	1.84 (2.01)
semimem	3.02 (2.38)	3.78 (3.09)	3.09 (3.41)	1.8 (0.38)	9.49 (3.11)	vas int	3.18 (2)	2.81 (3.33)	1.57 (0.95)	4.35 (6.28)	2.09 (2.33)
semiten	1.16 (1.11)	1.64 (1.63)	0.84 (1.33)	0.74 (0.4)	3.46 (1.6)	vas lat	4.95 (3.16)	4.49 (5.39)	2.39 (1.82)	7.3 (10.86)	3.48 (4.14)
bifemlh	2.85 (2.28)	3.83 (3.13)	3.03 (3)	1 (0.62)	7.9 (3.41)	med gas	6.34 (4.2)	10.24 (5.39)	9.77 (5.01)	8.4 (6.77)	14.22 (5.29)
bifemsh	5.71 (2.19)	7.07 (3.21)	5.85 (2.75)	5.48 (4.16)	8.74 (2.8)	lat gas	4.05 (3.09)	4.4 (3.57)	3.05 (2.66)	1.75 (1.61)	7.65 (2.34)
sar	1.41 (0.84)	1.63 (0.86)	1.28 (0.74)	1.7 (1.31)	1.7 (1.09)	soleus	16.54 (13.85)	19.18 (14.46)	12.96 (7.86)	10.69 (8.7)	33.75 (10.37)
add long	2.87 (2.79)	3.58 (3.48)	2.16 (3.13)	2.15 (2.05)	5.93 (2.63)	tib post	15.16 (9.16)	14.61 (11.42)	10.84 (7.72)	14.97 (13.55)	22.85 (9.01)
add brev	1.78 (1.88)	2.52 (2.91)	1.44 (2.23)	0.47 (0.33)	4.55 (2.87)	flex dig	2.1 (1.41)	2.22 (1.86)	1.28 (0.93)	2.91 (2.26)	3.55 (1.44)

Table 9

add mag	2.19 (1.86)	2.99 (3.41)	1.46 (1.96)	0.76 (0.49)	5.27 (3.87)	flex hal	2.35 (1.6)	2.39 (2.03)	1.19 (1.35)	2.19 (2.79)	3.97 (1.44)
tfl	1.92 (1.55)	2.22 (1.11)	1.67 (0.88)	2.25 (1.28)	1.94 (1.07)	tib ant	10.93 (4.28)	10.67 (5.62)	7.16 (4.18)	12.72 (8.34)	12.71 (4.98)
pect	0.63 (0.8)	1.36 (1.59)	0.67 (1.07)	2.23 (2.59)	2 (1.51)	per brev	5.23 (3.24)	5.93 (3.28)	5.3 (1.89)	3.71 (2.42)	4.75 (4.24)
grac	0.41 (0.53)	0.64 (0.8)	0.3 (0.58)	0.17 (0.12)	1.31 (0.85)	per long	9.94 (5.43)	11.36 (6.03)	10.9 (2.6)	8.16 (4.6)	9.68 (7.89)
glut max	3.92 (3.21)	4.9 (4.53)	2.99 (2.79)	1.16 (1.44)	7.16 (6.1)	per tert	2.45 (1.26)	2.49 (1.32)	2.85 (1)	2.34 (1.15)	1.83 (1.53)
iliacus	6.21 (6.44)	9.47 (6.41)	5.45 (4.05)	9.79 (8.03)	10.46 (4.9)	ext dig	7.21 (2.36)	7.05 (2.42)	7.7 (1.4)	7.34 (1.55)	5.88 (3.22)
psoas	6.17 (4.21)	10.25 (6.39)	6.14 (3.88)	11.82 (10.24)	11.29 (5.3)	ext hal	2.03 (0.85)	1.94 (1.04)	1.55 (0.87)	2.55 (1.31)	1.89 (1.51)
quad fem	2.68 (1.66)	3.16 (2.48)	2.59 (1.5)	3.41 (3.22)	3.91 (3.08)	ercspn	7.39 (5.13)	10.2 (8.92)	9.61 (9.08)	8.74 (8.46)	15.61 (13.33)
gem	0.55 (0.61)	1.12 (2.05)	0.59 (0.8)	1.01 (1.11)	1.34 (1.35)	intobl	3.64 (1.51)	4.48 (3.77)	3.74 (2.73)	4 (4.85)	5.67 (4.31)
peri	1.68 (2)	2.02 (2.15)	1.49 (1.8)	1.36 (1.96)	2.54 (2.42)	extobl	3.96 (2.33)	3.25 (2.99)	2.2 (2.21)	1.37 (0.52)	3.18 (2.05)

Table 10: The p-values of the muscles that showed significant difference (p-value ≤ 0.05) in at least one comparison of the maximum muscle force values among similarity-based groups for each stance phase.

Heel contact										
	Healthy vs Group A	Healthy vs Group B	Healthy vs Group C	Healthy vs Group D	Group A vs Group B	Group A vs Group C	Group A vs Group D	Group B vs Group C	Group B vs Group D	Group C vs Group D
glut med	0.00	0.75	0.02	0.67	0.79	0.46	0.00	0.23	0.29	0.01
glut min	0.01	1.00	0.17	0.87	0.61	0.75	0.05	0.37	0.86	0.09
semimem	0.00	1.00	0.03	0.81	0.06	0.73	0.47	0.09	0.94	0.28
semiten	0.00	1.00	0.96	1.00	0.32	0.97	0.32	0.99	1.00	0.99
bifemlh	0.00	0.34	0.03	0.92	0.66	0.88	0.11	0.52	0.93	0.21
bifemsh	0.00	0.31	0.93	0.93	1.00	0.99	0.02	1.00	0.22	0.77

Table 10

sar	0.00	0.00	0.11	0.89	0.31	0.89	0.00	1.00	0.00	0.06
add long	0.00	0.98	0.58	1.00	0.06	1.00	0.13	0.50	1.00	0.61
add brev	0.00	0.97	0.71	1.00	0.07	1.00	0.18	0.58	1.00	0.72
add mag	0.00	0.92	0.89	1.00	0.48	0.98	0.17	1.00	0.99	0.96
tfl	0.00	1.00	0.41	0.68	0.28	0.97	0.01	0.50	0.87	0.15
pect	0.00	0.99	0.54	1.00	0.55	1.00	0.14	0.78	0.98	0.52
grac	0.00	0.99	0.68	1.00	0.14	1.00	0.39	0.61	0.99	0.79
glut max	0.00	1.00	0.34	1.00	0.39	0.94	0.15	0.49	1.00	0.33
iliacus	0.05	0.65	0.32	0.62	0.04	0.83	0.03	0.10	1.00	0.10
psoas	0.05	0.40	0.34	0.48	0.01	0.85	0.02	0.07	1.00	0.08
quad fem	0.00	0.61	0.74	1.00	0.96	1.00	0.24	1.00	0.85	0.84
peri	0.00	0.59	0.25	1.00	0.99	0.91	0.14	0.85	0.63	0.27
rect fem	0.00	0.10	0.04	0.81	1.00	0.81	0.00	0.78	0.05	0.02
vas med	0.50	1.00	0.01	0.67	0.95	0.04	0.17	0.04	0.79	0.00
vas int	0.19	1.00	0.04	0.68	0.93	0.19	0.09	0.13	0.70	0.01
vas lat	0.38	1.00	0.26	0.72	0.97	0.59	0.17	0.48	0.75	0.10
med gas	0.00	0.01	0.27	1.00	0.95	0.99	0.03	1.00	0.05	0.27
lat gas	0.00	0.04	0.96	1.00	1.00	0.83	0.01	0.89	0.12	0.94
soleus	0.00	0.71	0.90	1.00	0.34	0.85	0.02	1.00	0.90	0.95
tib post	0.00	0.42	0.07	0.83	0.92	0.83	0.00	0.64	0.21	0.03
flex dig	0.00	0.32	0.64	0.66	1.00	1.00	0.01	1.00	0.09	0.28
flex hal	0.00	0.24	0.69	0.73	1.00	1.00	0.01	1.00	0.08	0.35
tib ant	0.00	0.01	0.65	0.91	0.91	1.00	0.01	0.98	0.01	0.44

Table 10

per brev	0.00	0.01	0.02	0.95	0.96	0.59	0.00	0.89	0.01	0.01
per long	0.00	0.04	0.02	0.79	0.97	0.37	0.01	0.73	0.02	0.01
per tert	0.00	0.01	0.00	0.99	1.00	0.38	0.00	0.64	0.02	0.00
ext dig	0.01	0.08	0.00	0.60	0.92	0.08	0.01	0.37	0.02	0.00
ext hal	0.00	0.00	0.09	1.00	0.96	0.95	0.03	1.00	0.06	0.20
intobl	0.00	0.64	0.22	0.78	0.99	0.87	0.02	0.79	0.29	0.09
					Foot flat					
	Healthy vs Group A	Healthy vs Group B	Healthy vs Group C	Healthy vs Group D	Group A vs Group B	Group A vs Group C	Group A vs Group D	Group B vs Group C	Group B vs Group D	Group C vs Group D
glut med	0.00	0.01	0.11	1.00	0.69	0.73	0.27	0.99	0.10	0.20
glut min	0.02	0.01	0.27	1.00	0.34	0.82	0.47	1.00	0.07	0.36
semimem	0.00	0.96	0.31	0.05	0.30	1.00	1.00	0.67	0.52	1.00
semiten	0.02	1.00	0.66	0.32	0.59	0.99	1.00	0.78	0.65	1.00
bifemlh	0.00	0.08	0.45	0.04	1.00	1.00	1.00	1.00	1.00	1.00
bifemsh	0.02	0.42	0.59	0.89	1.00	0.99	0.95	1.00	0.97	0.93
sar	0.00	0.00	0.14	0.78	0.22	0.84	0.86	1.00	0.14	0.60
add long	0.01	0.93	0.01	0.04	0.09	0.19	0.76	0.01	0.04	0.70
add brev	0.09	0.88	0.11	0.06	0.14	0.46	0.62	0.06	0.04	0.95
add mag	0.00	1.00	0.14	0.01	0.43	0.76	0.65	0.29	0.14	1.00
tfl	0.00	0.00	0.51	1.00	0.39	0.99	0.36	0.98	0.05	0.68
pect	0.03	1.00	0.07	0.48	0.31	0.43	1.00	0.08	0.54	0.60
grac	0.04	0.94	0.30	0.11	0.15	0.83	0.86	0.20	0.10	0.99
glut max	0.00	0.01	0.09	0.27	0.96	0.90	0.97	0.99	0.85	0.79

Table 10

quad fem	0.01	0.47	0.87	0.28	1.00	1.00	1.00	1.00	1.00	1.00
gem	1.00	0.95	1.00	1.00	0.87	1.00	1.00	1.00	0.98	1.00
rect fem	0.00	0.02	0.12	1.00	0.74	0.70	0.35	0.99	0.15	0.21
vas med	0.97	1.00	0.00	0.71	1.00	0.00	0.47	0.01	0.72	0.00
vas int	0.80	0.99	0.00	0.62	1.00	0.00	0.25	0.01	0.60	0.00
vas lat	0.70	1.00	0.01	0.76	1.00	0.03	0.32	0.05	0.76	0.00
med gas	0.00	0.27	0.02	0.27	0.99	0.50	0.99	0.45	1.00	0.45
lat gas	0.00	0.42	0.22	0.00	0.88	0.99	0.74	0.88	0.49	1.00
soleus	0.00	0.95	0.25	0.17	0.43	0.98	1.00	0.61	0.77	0.97
tib post	0.00	0.57	0.04	0.13	0.95	0.56	1.00	0.42	0.96	0.72
flex dig	0.00	0.75	0.00	0.39	0.96	0.05	1.00	0.05	0.99	0.10
flex hal	0.01	0.82	0.00	0.26	0.98	0.08	1.00	0.08	0.95	0.25
tib ant	0.00	0.11	0.57	0.76	0.98	1.00	0.96	1.00	0.88	0.96
per brev	0.00	0.00	0.01	0.55	0.12	0.7	0.36	1.00	0.01	0.21
per long	0.00	0.00	0.00	0.70	0.02	0.41	0.35	1.00	0.00	0.09
per tert	0.00	0.00	0.06	0.79	0.63	0.86	0.45	1.00	0.14	0.39
ext dig	0.06	0.07	0.17	0.90	0.70	0.63	0.13	0.98	0.05	0.10
ext hal	0.00	0.01	0.15	0.57	0.87	0.94	0.85	1.00	0.57	0.74
					Mid-stance					
	Healthy vs Group A	Healthy vs Group B	Healthy vs Group C	Healthy vs Group D	Group A vs Group B	Group A vs Group C	Group A vs Group D	Group B vs Group C	Group B vs Group D	Group C vs Group D
glut med	0.00	0.00	0.86	0.00	0.86	0.98	0.50	0.84	0.99	0.66
glut min	0.00	0.00	0.83	0.00	0.20	1.00	0.32	0.66	1.00	0.75

Table 10

semimem	0.00	1.00	1.00	0.00	0.48	0.90	0.00	1.00	0.00	0.03
semiten	0.18	1.00	1.00	0.00	0.60	0.99	0.00	1.00	0.00	0.12
bifemlh	0.00	0.29	0.99	0.00	1.00	0.94	0.00	0.96	0.01	0.03
bifemsh	0.91	0.97	1.00	0.00	1.00	1.00	0.00	1.00	0.02	0.19
sar	0.05	0.01	0.62	0.00	0.25	0.98	0.07	0.98	0.99	0.90
add long	0.44	0.99	1.00	0.00	0.63	1.00	0.00	0.99	0.00	0.04
add brev	0.29	1.00	1.00	0.00	0.75	0.97	0.00	1.00	0.00	0.01
add mag	0.10	1.00	1.00	0.00	0.48	0.98	0.00	1.00	0.00	0.02
tfl	0.00	0.00	0.58	0.21	0.09	1.00	1.00	0.84	0.44	1.00
pect	0.53	1.00	0.23	0.00	0.76	0.49	0.00	0.24	0.00	0.80
grac	0.05	0.99	1.00	0.00	0.29	0.92	0.00	1.00	0.00	0.02
glut max	0.00	0.03	1.00	0.00	0.95	0.81	0.10	0.65	0.70	0.15
iliacus	0.37	0.71	0.92	0.00	0.15	1.00	0.01	0.60	0.00	0.55
psoas	0.44	0.39	0.76	0.01	0.05	0.97	0.08	0.25	0.00	0.94
quad fem	0.96	0.96	0.99	0.00	1.00	0.95	0.00	0.93	0.00	0.00
peri	1.00	1.00	0.93	0.02	1.00	0.93	0.01	0.98	0.07	0.12
rect fem	0.01	0.02	0.26	0.14	0.71	0.88	0.98	1.00	0.98	0.98
med gas	0.55	0.99	0.99	0.00	0.99	1.00	0.02	1.00	0.06	0.45
lat gas	0.35	0.68	0.99	0.00	0.13	0.82	0.00	1.00	0.00	0.00
soleus	0.71	0.72	0.85	0.00	0.29	0.61	0.00	1.00	0.00	0.00
tib post	1.00	0.42	0.99	0.00	0.33	0.99	0.00	0.65	0.00	0.20
flex dig	0.93	0.69	0.13	0.00	0.40	0.21	0.00	0.04	0.00	0.86
flex hal	0.93	0.69	0.91	0.00	0.40	0.97	0.00	0.57	0.00	0.12

Table 10

tib ant	0.83	0.98	0.96	0.00	1.00	1.00	0.00	1.00	0.02	0.35
per brev	0.00	0.00	0.67	0.00	0.29	0.97	0.81	0.49	0.97	0.77
per long	0.00	0.00	0.46	0.00	0.08	1.00	0.40	0.58	0.97	0.83
per tert	0.00	0.00	0.90	0.01	0.43	0.98	0.92	0.63	0.97	0.88
ext dig	0.11	0.01	0.69	0.45	0.18	0.98	0.99	0.96	0.66	1.00
ext hal	0.00	0.00	0.31	0.00	0.62	0.99	0.36	1.00	1.00	0.98
ercspn	0.57	1.00	0.62	0.02	0.99	0.88	0.00	0.82	0.06	0.03
					Heel off					
	Healthy vs Group A	Healthy vs Group B	Healthy vs Group C	Healthy vs Group D	Group A vs Group B	Group A vs Group C	Group A vs Group D	Group B vs Group C	Group B vs Group D	Group C vs Group D
glut med	0.00	0.00	0.60	0.00	0.13	0.73	0.92	0.13	0.12	0.97
glut min	0.00	0.00	0.33	0.00	0.03	0.98	1.00	0.25	0.11	1.00
semimem	0.00	0.79	0.95	0.00	0.90	0.29	0.00	0.71	0.00	0.00
semiten	0.11	1.00	0.95	0.00	0.65	0.55	0.00	0.97	0.00	0.00
bifemlh	0.06	0.33	0.85	0.00	0.99	0.32	0.00	0.30	0.02	0.00
bifemsh	0.05	0.05	1.00	0.00	0.66	0.77	0.12	0.41	0.93	0.14
sar	0.00	0.00	0.38	0.20	0.49	1.00	1.00	0.98	0.63	0.99
add long	0.69	1.00	1.00	0.01	0.90	1.00	0.07	1.00	0.06	0.52
add brev	0.27	1.00	0.97	0.00	0.93	0.71	0.03	0.95	0.05	0.06
add mag	0.54	1.00	0.99	0.02	0.78	0.87	0.12	1.00	0.06	0.21
tfl	0.00	0.00	0.09	0.11	0.01	0.99	0.82	0.61	0.01	0.89
pect	0.08	1.00	0.13	0.01	0.82	0.53	0.23	0.29	0.13	1.00
grac	0.01	0.94	1.00	0.00	0.90	0.63	0.03	0.94	0.03	0.04

Table 10

glut max	0.00	0.00	1.00	0.00	0.69	0.18	0.54	0.06	1.00	0.05
psoas	0.01	0.96	0.49	0.08	0.11	0.98	0.91	0.37	0.10	1.00
quad fem	0.04	0.08	0.99	0.00	0.80	1.00	0.21	0.89	0.94	0.59
gem	0.05	0.90	0.99	0.36	0.98	0.99	0.99	1.00	0.95	0.98
peri	0.00	0.10	1.00	0.03	0.98	0.93	0.86	0.84	1.00	0.73
rect fem	0.00	0.00	0.01	0.29	0.21	0.76	0.36	1.00	0.03	0.26
vas med	0.13	1.00	0.02	0.99	0.81	0.14	0.43	0.07	0.99	0.03
vas int	0.07	1.00	0.01	0.98	0.82	0.12	0.30	0.06	0.97	0.01
vas lat	0.09	1.00	0.04	0.99	0.75	0.26	0.39	0.11	0.99	0.05
med gas	0.00	0.08	0.91	0.01	1.00	0.98	0.88	0.97	0.99	0.86
lat gas	0.99	0.90	0.83	0.00	0.77	0.73	0.01	0.99	0.01	0.03
soleus	0.97	0.98	0.86	0.00	0.88	0.74	0.00	0.98	0.00	0.02
tib post	0.87	0.56	1.00	0.17	0.84	1.00	0.04	0.95	0.03	0.69
flex dig	1.00	0.73	0.82	0.01	0.64	0.85	0.01	0.48	0.00	0.89
flex hal	1.00	0.62	1.00	0.01	0.67	1.00	0.00	0.99	0.00	0.22
per brev	0.00	0.00	0.92	0.33	0.32	0.82	0.72	0.28	0.12	1.00
per long	0.00	0.00	0.8	0.17	0.08	0.92	0.88	0.23	0.07	1.00
per tert	0.00	0.00	0.75	0.39	0.03	0.98	0.82	0.27	0.03	1.00
ext dig	0.00	0.00	0.68	0.97	0.07	1.00	0.7	0.73	0.03	0.92
ext hal	0.00	0.01	0.13	0.21	0.47	0.73	1.00	1.00	0.85	0.89
ercspn	0.02	0.48	0.99	0.00	1.00	0.98	0.03	0.99	0.18	0.25
					Toe off					
	Healthy	Healthy	Healthy	Healthy	Group A	Group A	Group A	Group B	Group B	Group C

Table 10

	vs Group A	vs Group B	vs Group C	vs Group D	vs Group B	vs Group C	vs Group D	vs Group C	vs Group D	vs Group D
semimem	0.48	1.00	0.92	0.00	0.94	0.66	0.00	0.94	0.00	0.00
semiten	0.25	0.96	0.98	0.00	0.37	0.74	0.00	1.00	0.00	0.01
bifemlh	0.22	1.00	0.72	0.00	0.89	0.30	0.00	0.73	0.00	0.00
bifemsh	0.03	1.00	1.00	0.01	0.64	0.81	0.31	1.00	0.10	0.28
add long	0.64	0.95	0.99	0.02	0.59	0.90	0.11	1.00	0.03	0.24
add brev	0.38	0.99	0.85	0.00	0.63	0.51	0.07	0.96	0.02	0.04
add mag	0.44	0.93	0.87	0.01	0.42	0.56	0.08	0.99	0.01	0.05
pect	0.01	1.00	0.15	0.01	0.46	0.72	0.53	0.27	0.11	1.00
grac	0.28	0.99	0.96	0.00	0.52	0.69	0.01	1.00	0.00	0.04
iliacus	0.01	1.00	0.80	0.20	0.22	1.00	0.99	0.75	0.28	1.00
psoas	0.00	1.00	0.29	0.03	0.12	0.98	0.98	0.40	0.17	1.00
med gas	0.00	0.19	0.93	0.00	1.00	0.95	0.07	0.99	0.19	0.26
lat gas	0.97	0.87	0.65	0.00	0.66	0.51	0.01	0.96	0.01	0.02
soleus	0.76	0.92	0.92	0.00	0.57	0.74	0.00	1.00	0.00	0.03
tib post	1.00	0.68	1.00	0.13	0.76	1.00	0.07	0.96	0.04	0.68
flex dig	0.99	0.52	0.88	0.04	0.34	0.93	0.07	0.43	0.01	0.96
flex hal	1.00	0.26	1.00	0.04	0.20	1.00	0.04	0.88	0.00	0.45

Table 11: The average and standard deviation of the maximum muscle force values of temporal component-based groups for each stance phase.

	Heel contact				Foot flat				Mid-stance	
	Healthy	Healthy	Affected-limb	Affected-limb	Healthy	Healthy	Affected-limb	Affected-limb	Healthy	Healthy
	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2
glut med	3.07 (3.2)	3.28 (3.59)	6.36 (4.25)	4.12 (3.72)	7.21 (4.81)	6.81 (4.67)	10.46 (4.59)	8.94 (4.35)	7.57 (4.24)	7.53 (4.23)
glut min	1.07 (1.76)	1.05 (1.77)	2.22 (2.25)	1.47 (2)	2.58 (2.51)	2.33 (2.17)	4.02 (2.64)	3.36 (2.58)	2.51 (1.76)	2.87 (2.25)
semimem	1.97 (2.78)	1.77 (2.15)	4.16 (2.78)	3.2 (2.38)	2.96 (3)	2.63 (2.54)	5.49 (3.36)	5.12 (3.76)	2.71 (2.8)	2.21 (2.49)
semiten	0.5 (0.59)	0.43 (0.6)	1.12 (1.06)	0.59 (0.55)	1.15 (1.08)	0.77 (0.88)	1.7 (1.59)	1.63 (1.78)	1.08 (1.22)	0.75 (0.87)
bifemlh	1.36 (1.64)	1.47 (1.73)	3.87 (2.63)	2.77 (2.19)	2.51 (2.04)	2.28 (2.11)	4.88 (3.08)	4.85 (3.22)	2.4 (1.99)	1.96 (1.76)
bifemsh	2.3 (1.58)	2.77 (2.28)	4.89 (3.81)	3.4 (3.27)	4.56 (2.59)	4.3 (2.73)	6.1 (3.71)	6.21 (3.71)	5.24 (3.21)	5.11 (3.08)
sar	0.48 (0.45)	0.58 (0.57)	1.22 (0.9)	0.89 (0.86)	1.04 (0.68)	1 (0.69)	1.64 (0.87)	1.57 (0.94)	1.26 (0.8)	1.36 (0.85)
add long	0.39 (0.39)	0.98 (1.59)	1.6 (1.99)	1.22 (1.58)	1.33 (1.49)	1.37 (1.82)	2.15 (2.07)	2.85 (2.81)	1.58 (1.89)	1.44 (1.83)
add brev	0.46 (1.19)	0.56 (0.85)	1.2 (1.51)	0.99 (1.37)	1.12 (1.57)	1.02 (1.39)	1.65 (1.84)	2.14 (2.41)	0.95 (1.17)	1.17 (1.55)
add mag	0.6 (1.13)	0.69 (0.76)	1.47 (1.38)	1.25 (1.11)	1.24 (1.49)	1.11 (1.29)	2.13 (1.92)	2.63 (2.53)	1.19 (1.24)	1.24 (1.41)
tfl	0.58 (0.45)	0.83 (0.85)	1.25 (1.09)	0.85 (1.01)	1.4 (1.08)	1.44 (0.97)	2.32 (1.34)	1.98 (1.34)	1.59 (1.18)	1.83 (1.33)
pect	0.28 (0.66)	0.15 (0.14)	0.62 (0.78)	0.43 (0.61)	0.48 (0.79)	0.36 (0.62)	0.8 (0.99)	0.98 (1.26)	0.47 (0.67)	0.56 (0.8)
grac	0.08 (0.05)	0.15 (0.29)	0.32 (0.48)	0.21 (0.38)	0.28 (0.44)	0.26 (0.37)	0.52 (0.7)	0.6 (0.84)	0.25 (0.35)	0.28 (0.42)
glut max	1.5 (1.7)	1.71 (2.27)	3.35 (3.25)	2.09 (2.43)	3.27 (3.54)	2.66 (2.87)	6.21 (3.53)	5.47 (3.41)	3.43 (3.03)	3.19 (3.12)
iliacus	2.54 (2.13)	2.65 (2.42)	4.32 (4.51)	2.83 (4.92)	4.98 (3.75)	4.66 (3.82)	5.65 (4.96)	7.39 (12.93)	4.91 (3.49)	4.66 (3.52)
psoas	2.85 (2.12)	3.25 (2.75)	4.69 (4.7)	2.97 (3.56)	5.52 (3.24)	5.55 (3.91)	6.5 (5.31)	6.82 (6.77)	5.47 (3.73)	5.97 (4)
quad fem	0.77 (0.95)	0.79 (0.84)	2.04 (2.47)	1.48 (1.34)	1.4 (1.13)	1.47 (0.91)	2.41 (2.28)	2.35 (1.67)	1.5 (0.98)	1.81 (0.92)
gem	0.73 (3.17)	0.11 (0.16)	0.89 (3.51)	0.23 (0.39)	1.02 (3.04)	0.31 (0.33)	0.96 (3.51)	0.54 (0.73)	0.45 (0.38)	0.35 (0.25)

Table 11

peri	0.67 (1.1)	0.57 (1.11)	1.59 (1.42)	0.85 (1.08)	1.8 (2)	1.38 (1.96)	2.19 (1.53)	1.88 (1.76)	2.11 (1.92)	1.81 (1.45)
rect fem	2.91 (2.81)	3.22 (3.42)	6.99 (5.34)	5.59 (4.97)	7.3 (4.65)	7.9 (4.75)	10.74 (5.81)	10.53 (5.7)	7.67 (4.52)	9.69 (6.24)
vas med	1 (0.99)	0.92 (0.62)	1.22 (0.97)	1.14 (1.27)	2.15 (1.9)	1.83 (1.79)	2.32 (1.97)	2.16 (2.43)	2.18 (1.49)	2.17 (1.54)
vas int	1.21 (1.26)	1.07 (0.75)	1.58 (1.28)	1.43 (1.5)	2.68 (2.14)	2.2 (1.9)	3.01 (2.42)	2.69 (2.67)	3.13 (1.8)	3.09 (1.6)
vas lat	1.88 (2.22)	1.62 (1.37)	2.34 (2.17)	2.12 (2.22)	4.05 (3.77)	3.26 (2.98)	4.52 (3.49)	4.16 (3.64)	4.01 (3.06)	3.97 (3.1)
med gas	1.49 (1.36)	1.59 (1.49)	4.32 (3.84)	2.65 (2.76)	4.26 (2.72)	3.74 (2.83)	8.31 (4.59)	6.24 (5.37)	6.77 (5.37)	5.81 (4.51)
lat gas	0.83 (0.93)	0.8 (1.4)	2.81 (2.64)	1.73 (1.71)	1.85 (1.81)	1.56 (1.7)	4.05 (2.88)	3.92 (3.3)	3.28 (2.89)	3.3 (2.44)
soleus	2.19 (1.51)	2.13 (2.56)	9.52 (10.37)	6.98 (8.54)	7.51 (6.64)	5.56 (5.74)	12.98 (9.88)	12.33 (8.82)	11.33 (9.17)	10.28 (8.44)
tib post	6.34 (4.42)	4.98 (4.08)	10.61 (7.48)	9.26 (7.36)	9.05 (3.84)	9.46 (3.52)	13.05 (6.67)	13.61 (6.51)	12.16 (7.68)	12.73 (7.32)
flex dig	0.7 (0.85)	0.88 (1.05)	1.5 (1.26)	1.14 (1.2)	1.11 (0.9)	1.3 (1.14)	1.88 (1.14)	1.93 (1.43)	1.4 (1.05)	1.46 (1.02)
flex hal	0.82 (1.15)	0.73 (1.02)	1.56 (1.37)	1.17 (1.27)	1.27 (1.17)	1.31 (1.27)	1.94 (1.32)	2.13 (1.47)	1.51 (1.37)	1.53 (1.25)
tib ant	5.56 (3.95)	5.97 (3.4)	9.26 (4.76)	7.97 (5.05)	7.8 (4.11)	7.9 (4.02)	10.42 (4.33)	10.33 (4.63)	7.21 (3.27)	8.79 (3.97)
per brev	1.78 (1.26)	1.72 (0.83)	3.71 (2.57)	3.21 (2.88)	2.88 (1.79)	2.34 (1.42)	5.54 (2.88)	4.96 (2.81)	3.25 (2.07)	3.16 (2.67)
per long	4.12 (2.37)	3.85 (1.86)	6.65 (4.34)	5.85 (4.57)	5.62 (2.86)	5.26 (2.53)	10.01 (4.9)	9.36 (4.88)	6.7 (3.17)	7.07 (5.04)
per tert	0.54 (0.52)	0.56 (0.71)	1.65 (1.22)	1.29 (1.34)	1.41 (1.02)	1.21 (1.01)	2.5 (1.24)	2.23 (1.41)	1.48 (1.02)	1.54 (1.16)
ext dig	3.41 (1.35)	3.06 (1.83)	4.86 (2.96)	4.14 (3.06)	5.3 (2.11)	5.15 (1.71)	6.45 (2.19)	5.84 (2.84)	4.95 (2.21)	5.5 (2.41)
ext hal	0.57 (0.54)	0.67 (0.7)	1.54 (1.01)	1.3 (1.19)	1.34 (0.85)	1.23 (0.83)	2.11 (0.88)	1.88 (1.01)	1.24 (0.81)	1.28 (0.8)
ercspn	2.89 (2.93)	3.67 (5.8)	5.18 (4.83)	4.4 (5.83)	7.52 (5.31)	7.79 (5.94)	7.77 (5)	7.05 (6.59)	8.21 (5.55)	7.55 (4.62)
intobl	1.46 (1.41)	1.51 (2.08)	3.11 (3.04)	2.3 (3.03)	2.67 (1.51)	2.63 (1.83)	3.52 (2.71)	2.98 (3.07)	3.48 (2.17)	3.04 (1.24)
extobl	1.6 (1.77)	1.37 (1.14)	2.25 (2.4)	1.69 (1.78)	2.67 (2.52)	1.98 (1.37)	2.48 (2.13)	2.57 (2.41)	3.75 (2.67)	3.54 (1.73)
	Mid-stance		Heel off				Toe off			
	Affected-limb	Affected-limb	Healthy	Healthy	Affected-limb	Affected-limb	Healthy	Healthy	Affected-limb	Affected-limb

Table 11

	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2	Gaussian 1	Gaussian 2
glut med	12.16 (5.53)	11.44 (5.01)	4.97 (2.83)	5.51 (3.12)	12.87 (5.81)	11.08 (5.68)	10.23 (6.64)	8.3 (4.2)	9.84 (5.54)	9.29 (4.97)
glut min	4.71 (2.85)	4.36 (2.54)	1.34 (0.94)	2.2 (2.24)	5.13 (2.83)	4.55 (2.68)	3.57 (2.89)	3.36 (2.63)	3.61 (2.57)	3.53 (2.43)
semimem	4.88 (4.82)	5.53 (5.04)	2.07 (1.69)	1.78 (1.92)	4.43 (4.1)	4.42 (4.89)	2.97 (2.01)	3.09 (2.85)	4.02 (3.22)	4.48 (3.97)
semiten	1.54 (1.95)	1.8 (2.06)	0.85 (0.91)	0.67 (1.31)	1.37 (1.7)	1.65 (2.14)	1.01 (0.8)	1.38 (1.43)	1.49 (1.5)	2.03 (1.9)
bifemlh	4.42 (4.32)	5.33 (4.27)	2.19 (1.3)	2.02 (1.85)	3.82 (3.78)	4.05 (4.36)	2.82 (2.06)	2.9 (2.6)	3.86 (3.1)	4.34 (3.74)
bifemsh	6.03 (4.07)	6.43 (4.24)	4.96 (3.51)	5.05 (3.88)	7.11 (3.83)	6.89 (4.09)	5.64 (1.82)	5.8 (2.65)	6.98 (3.31)	7.18 (3.06)
sar	1.79 (0.94)	1.87 (0.95)	1.16 (0.93)	1.23 (1.03)	1.96 (0.89)	1.89 (0.97)	1.37 (0.74)	1.46 (0.98)	1.59 (0.88)	1.62 (0.89)
add long	2.3 (3.2)	2.95 (3.63)	2.2 (2.43)	1.89 (2.03)	2.86 (3.6)	2.95 (3.61)	2.75 (2.92)	3.05 (2.64)	3.51 (3.47)	3.79 (3.4)
add brev	1.85 (2.71)	2.23 (3)	1.3 (1.13)	1.22 (1.46)	2.15 (2.88)	2.11 (2.8)	1.62 (1.72)	2.01 (2.1)	2.45 (2.91)	2.69 (2.89)
add mag	2.23 (2.99)	2.74 (3.41)	1.72 (1.09)	1.45 (1.5)	2.31 (3)	2.27 (3.02)	2.08 (1.85)	2.35 (1.9)	2.79 (3.28)	3.28 (3.57)
tfl	2.57 (1.37)	2.58 (1.35)	1.12 (0.66)	1.39 (1.23)	2.63 (1.39)	2.67 (1.36)	1.89 (1.5)	1.97 (1.63)	2.11 (1.11)	2.19 (1.07)
pect	0.82 (1.29)	1.16 (1.56)	0.46 (0.5)	0.62 (0.83)	1.08 (1.53)	1.22 (1.6)	0.48 (0.66)	0.83 (0.94)	1.28 (1.56)	1.52 (1.63)
grac	0.59 (0.95)	0.72 (0.93)	0.18 (0.22)	0.21 (0.44)	0.54 (0.79)	0.61 (0.87)	0.33 (0.45)	0.52 (0.61)	0.58 (0.77)	0.76 (0.86)
glut max	6.49 (4.29)	5.75 (3.99)	1.87 (1.75)	1.68 (1.55)	6.28 (4.47)	5.24 (3.85)	4.39 (3.56)	3.27 (2.56)	4.95 (4.8)	4.6 (4.35)
iliacus	6.05 (5.8)	7.12 (6.2)	7.26 (17.67)	7.44 (18.57)	8.01 (6.88)	8.55 (7.55)	6.71 (7.3)	5.53 (5.07)	8.87 (6.07)	9.62 (6.42)
psoas	6.84 (6.24)	7.72 (6.32)	4.58 (6.85)	6.73 (8.16)	8.77 (7.16)	9.55 (7.55)	5.89 (2.85)	6.55 (5.63)	9.58 (6.07)	10.61 (6.63)
quad fem	2.1 (2.59)	2.28 (2.36)	1.39 (1.07)	1.76 (1.62)	2.53 (2.3)	2.65 (1.77)	2.44 (1.57)	3.01 (1.76)	3.15 (2.58)	3.24 (2.34)
gem	0.99 (3.4)	0.74 (1.16)	0.2 (0.24)	0.2 (0.28)	1.09 (2.65)	0.77 (1.04)	0.52 (0.55)	0.59 (0.7)	1.17 (2.27)	0.98 (1.11)
peri	2.12 (1.91)	2.07 (2.26)	1.27 (1.39)	0.87 (0.79)	2.5 (2.12)	2.09 (2.39)	1.8 (2.31)	1.5 (1.49)	2.07 (2.2)	1.9 (2.04)
rect fem	12.14 (6.56)	12.62 (6.35)	5.06 (3.09)	8.52 (6.93)	15.08 (7.39)	13.95 (7.79)	10.89 (5.79)	11.85 (6.92)	14.18 (7.24)	13.11 (8.12)
vas med	2.36 (2.26)	2.47 (2.41)	1.49 (1.07)	2.1 (2.25)	2.42 (2.38)	2.8 (3.4)	2.08 (1.05)	3.12 (2.18)	1.84 (1.78)	2.73 (3.72)
vas int	3.06 (2.87)	3.1 (3.06)	1.8 (1.22)	2.52 (2.61)	3.14 (3.15)	3.42 (4.18)	2.65 (1.3)	3.92 (2.55)	2.29 (2.28)	3.21 (4.17)

Table 11

vas lat	4.68 (4.36)	5.04 (5.01)	2.87 (2.3)	4.13 (4.55)	4.89 (4.9)	5.5 (6.68)	4.16 (2.29)	6.03 (3.87)	3.65 (3.96)	5.18 (6.68)
med gas	8.26 (6.04)	8.49 (7.36)	6.69 (5.87)	5.75 (4.96)	11.15 (6.91)	11.65 (7.61)	6.71 (4.3)	5.82 (4.1)	10.06 (4.8)	11.19 (6.3)
lat gas	4.29 (4.33)	5.06 (4.62)	4.22 (3.76)	4.38 (3.61)	4.51 (4.01)	5.15 (4.2)	3.88 (2.89)	4.28 (3.39)	4.23 (3.42)	4.89 (3.68)
soleus	12.96 (13.02)	16.63 (14.82)	17.69 (16.68)	13.95 (13.36)	17.54 (13.98)	20.07 (16.91)	17.64 (14.51)	15.02 (13.02)	17.89 (12.12)	22.38 (16.76)
tib post	12.29 (10.72)	15.31 (10.83)	13.65 (9.29)	15.48 (9.52)	12.68 (11.48)	14.24 (11.64)	14.28 (8.96)	16.38 (9.46)	14.54 (10.99)	15.82 (11.57)
flex dig	1.56 (1.52)	2.14 (1.79)	1.66 (1.39)	1.82 (1.44)	1.69 (1.69)	2.21 (1.91)	2.03 (1.5)	2.2 (1.28)	2.06 (1.67)	2.61 (2)
flex hal	1.7 (1.71)	2.21 (2.01)	1.92 (1.72)	2.02 (1.66)	1.86 (1.97)	2.23 (2.13)	2.33 (1.65)	2.39 (1.56)	2.2 (1.88)	2.75 (2.2)
tib ant	8.37 (4.64)	10.09 (3.87)	8 (4.42)	9.39 (4.54)	8.41 (5.85)	9.71 (4.54)	10.73 (3.61)	11.2 (5.14)	10 (5.62)	11.45 (5.57)
per brev	6.53 (2.86)	5.79 (3.06)	2.87 (2.12)	3.67 (3.57)	6.6 (3.17)	5.75 (3.47)	5.16 (2.96)	5.33 (3.65)	6.07 (3.1)	5.12 (3.45)
per long	12.49 (5.35)	11.52 (5.74)	5.57 (4.12)	6.82 (6.33)	12.76 (6.12)	11.2 (6.58)	10.04 (4.97)	9.79 (6.11)	11.61 (5.6)	10.22 (6.36)
per tert	2.53 (1.21)	2.31 (1.18)	1.03 (0.96)	1.31 (1.37)	2.51 (1.26)	2.02 (1.36)	2.39 (1.08)	2.53 (1.48)	2.68 (1.21)	2.13 (1.41)
ext dig	6.64 (2.61)	6.03 (2.53)	3.66 (2.57)	4.77 (3.96)	6.46 (2.87)	5.33 (2.79)	6.97 (1.89)	7.54 (2.9)	7.38 (2.2)	6.47 (2.64)
ext hal	1.98 (0.78)	1.91 (0.8)	1.14 (0.87)	1.49 (1.12)	1.91 (0.92)	1.86 (0.85)	1.92 (0.79)	2.19 (0.93)	1.88 (1.01)	1.96 (1.2)
ercspn	7.53 (6.04)	6.81 (5.99)	5.28 (4.72)	3.99 (3.08)	8.52 (6.61)	7.83 (7.05)	7.81 (5.93)	6.8 (3.8)	10.92 (9.51)	10.2 (9.46)
intobl	3.78 (2.89)	3.44 (2.55)	3.56 (1.56)	3.15 (1.47)	4.46 (3.27)	3.88 (2.86)	3.9 (1.48)	3.27 (1.51)	4.92 (3.71)	3.92 (3.76)
extobl	2.79 (2.2)	2.68 (2.18)	4.22 (2.48)	3.7 (2.03)	3.35 (2.24)	2.89 (2.14)	4.39 (2.34)	3.36 (2.22)	3.43 (3.1)	2.58 (2.28)

Table 12: The p-values of the muscles that showed significant difference (p-value ≤ 0.05) in at least one comparison of the maximum muscle force values among temporal component-based groups for each stance phase. HG stands for Gaussians of healthy gait and AG stands for Gaussians of the gait of hip OA patients.

	Heel contact						Foot flat					
	HG 1 vs HG 2	HG 1 vs AG 1	HG 1 vs AG 2	HG 2 vs AG 1	HG 2 vs AG 2	AG 1 vs AG 2	HG 1 vs HG 2	HG 1 vs AG 1	HG 1 vs AG 2	HG 2 vs AG 1	HG 2 vs AG 2	AG 1 vs AG 2
glut med	1.00	0.00	0.59	0.00	0.8	0.01	0.99	0.00	0.31	0.00	0.22	0.27
glut min	1.00	0.03	0.8	0.06	0.82	0.19	0.98	0.03	0.49	0.02	0.33	0.49
semimem	0.99	0.00	0.13	0.00	0.10	0.18	0.98	0.00	0.01	0.00	0.01	0.93
semiten	0.98	0.00	0.96	0.00	0.84	0.00	0.75	0.26	0.45	0.03	0.08	0.99
bifemlh	1.00	0.00	0.02	0.00	0.08	0.04	0.99	0.00	0.00	0.00	0.00	1.00
bifemsh	0.94	0.00	0.38	0.02	0.85	0.05	0.99	0.12	0.12	0.09	0.09	1.00
sar	0.95	0.00	0.07	0.00	0.36	0.10	1.00	0.00	0.02	0.00	0.02	0.97
add long	0.49	0.00	0.09	0.35	0.93	0.59	1.00	0.25	0.01	0.40	0.03	0.30
add brev	0.99	0.03	0.28	0.16	0.56	0.82	1.00	0.53	0.07	0.48	0.07	0.50
add mag	0.99	0.00	0.06	0.02	0.20	0.76	0.99	0.12	0.01	0.11	0.01	0.51
tfl	0.74	0.00	0.55	0.21	1.00	0.10	1.00	0.00	0.15	0.01	0.29	0.45
pect	0.87	0.05	0.72	0.01	0.29	0.38	0.96	0.41	0.11	0.22	0.05	0.76
grac	0.86	0.01	0.35	0.22	0.91	0.43	1.00	0.28	0.11	0.32	0.14	0.90
glut max	0.99	0.00	0.74	0.03	0.94	0.05	0.90	0.00	0.02	0.00	0.00	0.64
iliacus	1.00	0.13	0.99	0.27	1.00	0.19	1.00	0.97	0.48	0.94	0.46	0.61
psoas	0.98	0.08	1.00	0.34	0.99	0.06	1.00	0.8	0.68	0.86	0.75	0.99
quad fem	1.00	0.00	0.26	0.01	0.38	0.32	1.00	0.03	0.07	0.10	0.17	1.00
peri	0.99	0.00	0.90	0.00	0.79	0.01	0.79	0.68	1.00	0.18	0.64	0.77

Table 12

rect fem	0.99	0.00	0.04	0.00	0.14	0.34	0.97	0.01	0.03	0.10	0.19	1.00
med gas	1.00	0.00	0.27	0.00	0.44	0.01	0.97	0.00	0.16	0.00	0.08	0.04
lat gas	1.00	0.00	0.17	0.00	0.21	0.02	0.97	0.00	0.00	0.00	0.00	0.99
soleus	1.00	0.00	0.03	0.00	0.06	0.31	0.81	0.01	0.05	0.00	0.01	0.98
tib post	0.85	0.01	0.17	0.00	0.03	0.68	0.99	0.00	0.00	0.03	0.02	0.95
flex dig	0.93	0.00	0.30	0.08	0.79	0.31	0.93	0.01	0.01	0.14	0.12	1.00
flex hal	0.99	0.02	0.59	0.02	0.48	0.34	1.00	0.07	0.02	0.17	0.05	0.87
tib ant	0.99	0.00	0.07	0.01	0.26	0.41	1.00	0.02	0.04	0.05	0.09	1.00
per brev	1.00	0.00	0.02	0.00	0.04	0.64	0.83	0.00	0.00	0.00	0.00	0.60
per long	0.99	0.01	0.17	0.01	0.14	0.67	0.99	0.00	0.00	0.00	0.00	0.84
per tert	1.00	0.00	0.01	0.00	0.03	0.28	0.92	0.00	0.01	0.00	0.00	0.62
ext dig	0.95	0.03	0.58	0.01	0.32	0.44	0.99	0.07	0.70	0.07	0.60	0.49
ext hal	0.98	0.00	0.00	0.00	0.03	0.51	0.97	0.00	0.03	0.00	0.02	0.52
ercspn	0.93	0.11	0.51	0.54	0.93	0.83	1.00	1.00	0.98	1.00	0.95	0.90
intobl	1.00	0.01	0.48	0.04	0.61	0.35	1.00	0.35	0.94	0.42	0.94	0.66
extobl	0.97	0.37	1.00	0.21	0.91	0.42	0.61	0.97	1.00	0.76	0.69	1.00
	Mid-stance			Mid-stance			Heel off					
	HG 1 vs HG 2	HG 1 vs AG 1	HG 1 vs AG 2	HG 2 vs AG 1	HG 2 vs AG 2	AG 1 vs AG 2	HG 1 vs HG 2	HG 1 vs AG 1	HG 1 vs AG 2	HG 2 vs AG 1	HG 2 vs AG 2	AG 1 vs AG 2
glut med	1.00	0.00	0.00	0.00	0.01	0.86	0.98	0.00	0.00	0.00	0.00	0.21
glut min	0.95	0.00	0.00	0.01	0.06	0.88	0.52	0.00	0.00	0.00	0.00	0.57
semimem	0.97	0.06	0.01	0.03	0.01	0.84	0.99	0.01	0.02	0.01	0.02	1.00
semiten	0.88	0.57	0.23	0.19	0.06	0.85	0.97	0.41	0.12	0.25	0.07	0.81

Table 12

bifemlh	0.97	0.04	0.00	0.02	0.00	0.54	1.00	0.09	0.06	0.10	0.07	0.98
bifemsh	1.00	0.75	0.48	0.72	0.48	0.94	1.00	0.03	0.10	0.09	0.19	0.99
sar	0.98	0.02	0.01	0.15	0.09	0.96	0.99	0.00	0.00	0.00	0.02	0.98
add long	1.00	0.64	0.15	0.59	0.15	0.62	0.98	0.75	0.71	0.56	0.52	1.00
add brev	0.99	0.27	0.07	0.61	0.27	0.82	1.00	0.32	0.42	0.34	0.43	1.00
add mag	1.00	0.23	0.04	0.37	0.10	0.73	0.98	0.68	0.76	0.47	0.55	1.00
tfl	0.89	0.00	0.00	0.07	0.08	1.00	0.84	0.00	0.00	0.00	0.00	1.00
pect	0.99	0.52	0.05	0.80	0.18	0.42	0.96	0.10	0.04	0.42	0.24	0.94
grac	1.00	0.16	0.04	0.31	0.10	0.84	1.00	0.06	0.02	0.17	0.08	0.94
glut max	1.00	0.00	0.03	0.00	0.03	0.73	1.00	0.00	0.00	0.00	0.00	0.38
iliacus	1.00	0.72	0.22	0.66	0.22	0.69	1.00	0.99	0.96	1.00	0.98	0.99
psoas	0.99	0.63	0.25	0.91	0.56	0.82	0.67	0.03	0.01	0.62	0.39	0.94
quad fem	0.94	0.50	0.33	0.93	0.8	0.97	0.87	0.02	0.01	0.28	0.21	0.99
peri	0.93	1.00	1.00	0.89	0.94	1.00	0.86	0.01	0.21	0.00	0.05	0.66
rect fem	0.57	0.00	0.00	0.30	0.19	0.97	0.20	0.00	0.00	0.00	0.01	0.81
med gas	0.93	0.64	0.58	0.30	0.27	1.00	0.95	0.01	0.00	0.00	0.00	0.98
lat gas	1.00	0.59	0.17	0.70	0.26	0.72	1.00	0.98	0.71	1.00	0.85	0.82
soleus	0.99	0.92	0.20	0.78	0.14	0.37	0.78	1.00	0.89	0.73	0.35	0.81
tib post	1.00	1.00	0.46	1.00	0.70	0.34	0.91	0.97	0.99	0.67	0.97	0.86
flex dig	1.00	0.95	0.10	0.99	0.22	0.14	0.98	1.00	0.43	0.99	0.77	0.34
flex hal	1.00	0.94	0.23	0.97	0.34	0.36	1.00	1.00	0.89	0.98	0.97	0.74
tib ant	0.44	0.50	0.01	0.97	0.56	0.1	0.71	0.98	0.41	0.84	0.99	0.50
per brev	1.00	0.00	0.00	0.00	0.00	0.46	0.75	0.00	0.00	0.00	0.03	0.45

Table 12

per long	0.99	0.00	0.00	0.00	0.00	0.73	0.85	0.00	0.00	0.00	0.01	0.48
per tert	1.00	0.00	0.01	0.00	0.03	0.74	0.82	0.00	0.00	0.00	0.09	0.16
ext dig	0.82	0.00	0.20	0.19	0.82	0.54	0.47	0.00	0.05	0.06	0.86	0.17
ext hal	1.00	0.00	0.00	0.00	0.01	0.97	0.47	0.00	0.00	0.18	0.33	0.99
ercspn	0.97	0.94	0.68	1.00	0.95	0.91	0.84	0.04	0.22	0.01	0.04	0.92
intobl	0.90	0.94	1.00	0.57	0.91	0.89	0.93	0.36	0.95	0.14	0.67	0.64
extobl	0.98	0.15	0.13	0.46	0.39	0.99	0.80	0.22	0.03	0.90	0.43	0.67
	Toe off											
	HG 1 vs HG 2	HG 1 vs AG 1	HG 1 vs AG 2	HG 2 vs AG 1	HG 2 vs AG 2	AG 1 vs AG 2						
glut med	0.52	0.99	0.86	0.61	0.88	0.95						
glut min	0.99	1.00	1.00	0.98	0.99	1.00						
semimem	1.00	0.38	0.13	0.58	0.27	0.86						
semiten	0.78	0.39	0.01	0.99	0.28	0.22						
bifemlh	1.00	0.34	0.10	0.52	0.21	0.82						
bifemsh	1.00	0.11	0.07	0.29	0.21	0.98						
sar	0.98	0.62	0.55	0.92	0.87	1.00						
add long	0.98	0.65	0.45	0.92	0.78	0.97						
add brev	0.94	0.41	0.24	0.88	0.70	0.96						
add mag	0.98	0.64	0.25	0.92	0.58	0.82						
tfl	0.99	0.84	0.69	0.97	0.89	0.98						
pect	0.76	0.02	0.00	0.48	0.16	0.78						
grac	0.74	0.32	0.03	0.98	0.53	0.55						

Table 12

glut max	0.73	0.91	1.00	0.30	0.55	0.97
iliacus	0.89	0.33	0.15	0.09	0.04	0.92
psoas	0.97	0.01	0.00	0.09	0.02	0.76
quad fem	0.76	0.40	0.37	0.99	0.98	1.00
peri	0.95	0.92	1.00	0.64	0.86	0.97
rect fem	0.95	0.11	0.49	0.49	0.89	0.85
med gas	0.90	0.01	0.00	0.00	0.00	0.63
lat gas	0.97	0.96	0.52	1.00	0.88	0.71
soleus	0.89	1.00	0.42	0.81	0.14	0.31
tib post	0.87	1.00	0.91	0.87	1.00	0.91
flex dig	0.98	1.00	0.39	0.98	0.74	0.28
flex hal	1.00	0.99	0.74	0.97	0.87	0.39
tib ant	0.99	0.90	0.92	0.74	1.00	0.43
per brev	1.00	0.51	1.00	0.75	0.99	0.38
per long	1.00	0.54	1.00	0.51	0.99	0.56
per tert	0.97	0.69	0.79	0.96	0.56	0.09
ext dig	0.79	0.84	0.77	0.99	0.25	0.17
ext hal	0.72	1.00	1.00	0.55	0.79	0.98
ercspn	0.97	0.26	0.55	0.13	0.33	0.97
intobl	0.87	0.39	1.00	0.10	0.84	0.31
extobl	0.43	0.28	0.01	1.00	0.62	0.30

IV Discussion

4.1 Comparison of the identified gait types

4.1.1 Characteristics of the similarity-based groups

To compare and evaluate the characteristics of the identified groups, the average of the first temporal and spatial components of healthy gait (projection components) was used to calculate the component scores. The first components are the principal components with the largest eigenvalue, which means that the first components contain the largest amount of variance or information of the original data [86][87]. The first temporal and spatial components of the healthy gait explained 56.5% of the data variance. The shapes of projection components are shown in Fig. 10. In the figure, GRF stands for ground reaction force, MO stands for moment, and x, y, and z stand for the medial-lateral, anterior-posterior, and vertical directions, respectively. The temporal projection component had positive values at 17–85% stance and negative values at the rest of the stance phase, with two positive peaks at 29% stance and 73% stance. The spatial projection component had the largest value at the medial-lateral GRF.

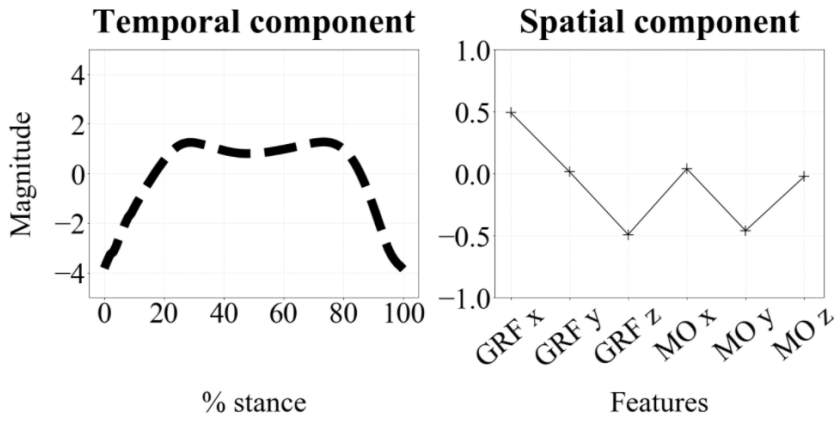

Figure 10: The means of the first principal components of the gait patterns of healthy subjects (projection components).

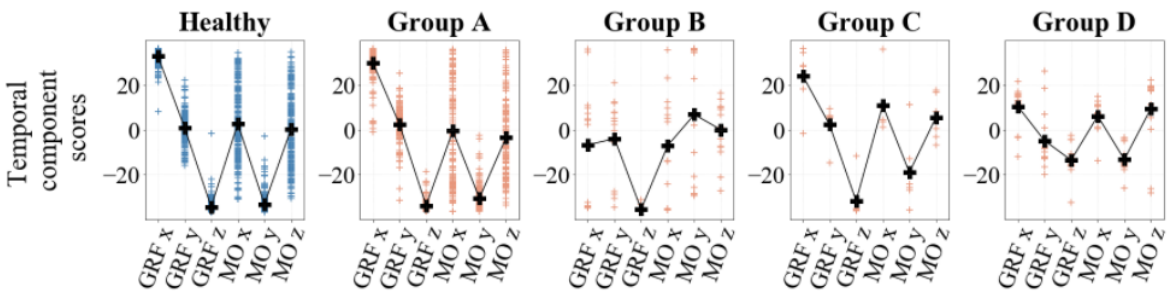

Figure 11: Temporal component scores of gait trials of healthy subjects and the affected limb of hip OA patients.

The component scores of gait trials were obtained by projecting the gait measurements onto the

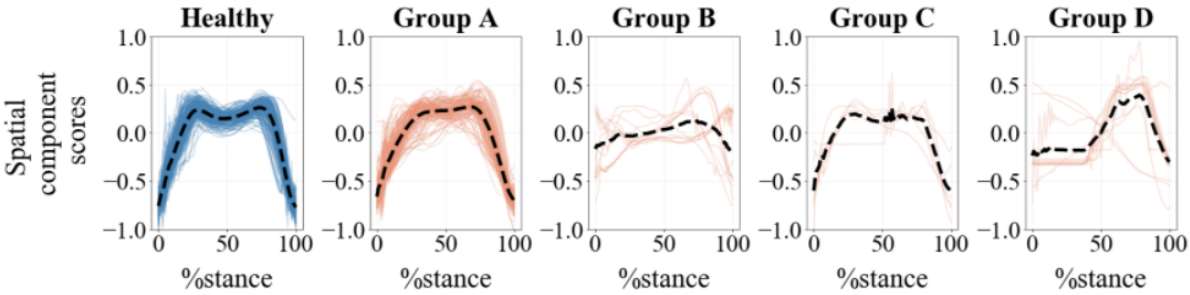

Figure 12: Spatial component scores of gait trials of healthy subjects and the affected limb of hip OA patients.

projection components. The temporal component scores, which are the gait data projected onto the temporal projection component, are shown in Fig. 11. The spatial component scores, which are the gait data projected onto the spatial projection component, are shown in Fig. 12. In the figures, GRF stands for ground reaction force, MO stands for moment, and x, y, and z stand for medial-lateral, anterior-posterior, and vertical direction, respectively, and the black markers indicate the average values for each group. Using the component scores, the differences of the gait features of each group in both latent temporal and spatial aspects can be explained.

The meaning of the projection components, which are the average principal components of healthy subjects used for calculating component scores, can be defined from the magnitude of the principal components [52]. Then, the features of the identified gait groups can be defined and compared using the component scores with the derived meanings of the projection components.

The temporal projection component represents the amount of activity in the middle part of the stance since the projection component captured the difference between the middle and early/latter part of the stance. The temporal component scores of the healthy gait group indicate that this group showed large force and moment along the medial-lateral and vertical directions in the middle part of the stance, whereas the force and moment along the anterior-posterior direction were relatively small. This implies that the group was highly stable and less likely to falter during the middle part of the stance. The temporal component scores of group A had shapes similar to those of the healthy gait group. However, the magnitude of the scores that peaked in the healthy gait group was slightly smaller in group A. This implies that group A showed the gait pattern similar to the healthy group in general, but the force and moment required to maintain stability were slightly weaker in group A. The temporal component scores of group B indicate that the group had small force and moment along the medial-lateral direction in the middle part of the stance. This implies that the group is less stable in the medial-lateral direction than the other groups during the middle part of the stance. The temporal component scores of group C had shapes similar to those of the healthy group, but the magnitude of the scores that peaked in the healthy gait group was slightly smaller in group C than in the healthy gait group. Moreover, the decrease in

magnitude was larger than that in group A, and the decrease in moment was larger than that of GRF. This implies that group C was less stable than the healthy gait group and group A during the middle part of the stance. In particular, it can be assumed that the group lost more moment than force to maintain stability. The temporal component scores of group D had shapes similar to those of the healthy gait group but with a smaller magnitude in general. This implies that the group did not exert enough force and moment for maintaining stability. Moreover, compared with the other groups, the force used to stand upright during the middle part of the stance was weak. Overall, group A was the most stable group, group B was had the weakest stabilizing force and moment, group C was weak in terms of the stabilizing moment, and group D was the group that did not exert enough force and moment overall.

The spatial projection component captured the force and moment along the medial-lateral direction. The healthy gait group's spatial component scores show that the force and moment along the medial-lateral direction peaked at the early and late middle part of the stance. The spatial component scores of group A show the force and moment along the medial-lateral direction peaked in the late middle part of the stance. The spatial component scores of group B imply that the force and moment along the medial-lateral direction were relatively weak in general. The spatial component scores of group C imply that the force and moment along the medial-lateral direction peaked at the early middle part of the stance. Finally, the spatial component scores of group D imply that the force and moment along the medial-lateral direction were weak at the early half part of the stance and started to affect gait at the late half part of the stance. Overall, the four groups differed in the time periods when the force and moment along the medial-lateral direction were effectively exerted.

From the temporal and spatial component scores, the characteristics of the similarity-based groups can be inferred. Group A was the most stable among the three groups, with the highest tendency to maintain medial-lateral stability in the late middle part of the stance. This is reasonable since the healthy gait group showed temporal and spatial component scores similar to those of group A. Group B was the least stable and lacked the tendency to maintain medial-lateral stability in the middle part of the stance. Group C lacked the ability to maintain stability using moment with the largest effort to maintain medial-lateral stability in the early middle part of stance. Group D did not exert an appropriate amount of force and moment to maintain stability in general and the effort to maintain medial-lateral stability seemed to be effectively exerted only on the latter half of the stance.

Therefore, it is shown that the gait characteristics of patients with hip OA can be different by subjects in terms of temporal and spatial aspects. It is also shown that the different types of gait can be distinguished and grouped using the similarity of the temporal and spatial components of the gait measurements. The similarity-based groups and the quantitative classification criteria used to distinguish and identify the groups can help understand the conditions and track gait changes of patients with hip

OA.

4.1.2 Characteristics of the component-based groups

The characteristics of the component-based groups can be inferred from the Gaussian center positions of each group. Each gait group's center positions indicate the tendency or trend of the gait type towards each feature, so a large magnitude of the center positions indicate a high tendency toward the corresponding features.

The spatial characteristics of healthy gait can be inferred from the comparison of the Gaussians of healthy gait. The center positions of the 5 Gaussians of healthy gait are similar for medial-lateral GRF, vertical GRF, and anterior-posterior moment but dispersed for anterior-posterior GRF, medial-lateral moment, and vertical moment. This implies that the medial-lateral features of healthy gait are similar to one another, while the anterior-posterior features of healthy gait are different from one another.

The spatial characteristics of affected-limb gait can be inferred from the comparison of the Gaussians of affected-limb gait. Unlike the Gaussians of healthy gait, the center positions of the 5 Gaussians of affected-limb gait are different for all force plate measurement variables, which are the GRF and moment in medial-lateral, anterior-posterior, and vertical directions. This implies that the affected-limb gait is distinguishable with both medial-lateral and anterior-posterior features. The spatial characteristics of individual component-based groups of affected-limb gait can be inferred from comparing the corresponding Gaussians of affected-limb gait and the Gaussians of healthy gait. Among the spatial component-based groups of affected-limb gait, Gaussian 1 and Gaussian 5 are the Gaussians or groups that are the most similar to the Gaussians of the spatial components of healthy gait. The similarities between the Gaussians of spatial components of healthy gait and affected-limb gait can be inferred from the root-mean-square deviation (RMSD) of the Gaussian center positions as shown in table 13. The Gaussians with the smallest RMSD of center positions were Gaussian 1 of healthy gait and Gaussian 5 of affected-limb gait with the RMSD value of 0.10, and the Gaussians with the second smallest RMSD of center positions were Gaussian 2 of healthy gait and Gaussian 1 of affected-limb gait with the RMSD value of 0.16. Therefore, Gaussian 1 and Gaussian 5 of the affected-limb gait are the groups that are similar to healthy gait, with the difference between two groups lying on the movement along the anterior-posterior direction. The Gaussian 2 is the group that is also similar to healthy gait but is slightly different in the medial-lateral direction. The Gaussian 3 and 4 are the groups that are different from healthy gait in the movement along the medial-lateral direction, with the difference between two groups lying on the movement along the anterior-posterior direction.

A similar analysis can be done to the temporal component-based groups. The difference between the two temporal component-based groups of healthy gait is expressed the most when the Gaussian center

		Healthy				
		Gaussian 1	Gaussian 2	Gaussian 3	Gaussian 4	Gaussian 5
Affected-limb	Gaussian 1	0.36	0.10	0.22	0.31	0.32
	Gaussian 2	0.17	0.47	0.26	0.35	0.48
	Gaussian 3	0.62	0.51	0.62	0.55	0.46
	Gaussian 4	0.68	0.55	0.65	0.74	0.76
	Gaussian 5	0.16	0.39	0.33	0.08	0.24

Table 13: The root-mean-square deviation of the Gaussian center positions of spatial components of healthy subjects and patients with hip OA.

		Healthy	
		Gaussian 1	Gaussian 2
Affected-limb	Gaussian 1	0.03	0.06
	Gaussian 2	0.11	0.05

Table 14: The root-mean-square deviation of the Gaussian center positions of temporal components of healthy subjects and patients with hip OA.

positions of the two groups peaked at. The difference between the two temporal component-based groups of affected-limb gait is also expressed the most at similar time instances to those of the healthy gait. Between the two temporal component-based groups of affected-limb gait, Gaussian 1 of healthy gait is more similar to healthy gait than Gaussian 2 with the smallest RMSD value of Gaussian center positions of 0.03 as in table 14.

4.1.3 Comparison of the similarity-based and component-based groups

The similarity-based groups and component-based groups were obtained through two different methods. The similarity-based groups were derived and characterized by the similarity of each gait trial to healthy gait. The component-based groups were derived through the clustering of the temporal and spatial component values.

One main common feature of the similarity-based grouping method and component-based grouping method is that the two methods show similar results in distinguishing the affected-limb gait that is highly similar to healthy gait. Among the similarity-based groups of affected-limb gait, group A and group D are the groups which are similar to healthy gait in spatial aspect. Among the spatial component-based groups of affected-limb gait, Gaussian 1 and Gaussian 5 are the Gaussians or groups that are the most similar to the Gaussians of the spatial components of healthy gait. From the gait trials in group A and group D of the similarity-based groups, 91.67% of the gait trials belonged to the Gaussian 1 and Gaussian 2 of the spatial component-based groups of affected-limb gait. Similarly, among the temporal component-based groups of affected-limb gait, group A and group B are the groups that are similar to healthy gait in the temporal aspect. Among the temporal component-based groups of affected-limb gait, Gaussian 1 is the Gaussian or group most similar to the Gaussians of the temporal components of healthy gait. From the gait trials in group A and group B of the similarity-based groups, 72.92% of the

gait trials belonged to the Gaussian 1 of the temporal component-based group of affected-limb gait. The results imply that the similarity-based grouping method and component-based grouping method similarly identify and distinguish the affected-limb gait trials similar to the healthy gait, which is reasonable since the inherent characteristics of gait trials do not change with the methods used to analyze and group them. Thus, the results show that both methods yield reasonable results in grouping affected-limb gait trials that are similar to healthy gait.

One main difference between the similarity-based grouping method and component-based grouping method is that the component-based grouping method yields a more specific differentiation of affected-limb gait. The similarity-based groups are based on the overall similarity of temporal and spatial components of gait trials. The component-based groups are based on the individual similarity of temporal and spatial components of gait features, which are the GRF and moment for the spatial components and time instances for the temporal components. The difference is clearly shown in the number of similarity-based groups and component-based groups in spatial aspects. The similarity-based groups can be divided into 2 groups in spatial aspect, in which the first group includes group A and group D and the second group includes group B and group C. The difference between these two groups are explained using the overall similarity to healthy gait or by the corresponding component scores which are explained as characteristics related to the medial-lateral movement. On the other hand, the affected-limb gait is divided into 5 different spatial component-based groups, and the characteristics of each group can be inferred from the center positions of the corresponding Gaussians. Therefore, component-based groups are more specific grouping results than the similarity-based groups. Moreover, it is possible to define the similar or dissimilar part between different gait trials with the component-based grouping method, while it is difficult to point out the specific part of the difference with the similarity-based grouping method.

4.2 Physical implications of the gait types

4.2.1 Muscle forces of the gait types in spatial aspect

From the comparison of the maximum muscle forces during stance of each similarity-based group shown in table 5 and table 6, it is shown that the muscles that showed a significant difference between the healthy gait group and group A were the hip, thigh, and trunk muscles related with balance and stability (e.g., glut med, glut min, tfl, vas int, extobl) [88][89][90][91]. The muscle forces in healthy gait group were larger than those of group A. Muscles that showed a significant difference between the healthy gait group and group B were the hip, thigh, and trunk muscles related to balance and stability (e.g., glut med, glut min, tfl, vas int, vas lat, extobl) and ankle muscles (e.g., flex hal, tib ant) [88][89][90][91][92]. The muscle forces in healthy gait group and group A were larger than those of group B. There were no muscles that showed a significant difference between the healthy gait group and group C. This is

assumed to be because the number of gait trials in group C was too small compared to those in the healthy gait group to yield significant differences in muscle forces. Muscles that showed a significant difference between the healthy gait group and group D were focused on the thigh muscles related to stability (e.g., semimem, semiten, bifemlh) [93]. The muscle forces in the healthy gait group were smaller than those of group D for the muscles. The comparison among the affected-limb gait groups showed that group A, group B, and group C did not show a significant difference in maximum muscle forces. On the other hand, group D showed a significant difference in maximum muscle forces with the other affected-limb gait groups. Muscles that showed a significant difference between group A and group D were focused on the thigh and calf muscles related to stability and balance (e.g., semimem, semiten, bifemlh, soleus) [93][94]. The muscle forces in group D were larger than those of group A. Muscles that showed a significant difference between group B and group D were focused on the thigh muscles related to stability (e.g., semimem, semiten, bifemlh) [93] and ankle muscles (e.g., tib post, flex dig, flex hal, tib ant). The muscle forces in group D were larger than those of group B. Muscles that showed a significant difference between group C and group D were focused on the thigh and calf muscles related to stability and balance (e.g., semimem, semiten, bifemlh, grac, lat gas, soleus) [93][94]. The muscle forces in group D were larger than those of group C.

Several notable points can be derived from the maximum muscle forces of the similarity-based groups. First, it is shown that there is a distinct difference between the healthy gait and the affected-limb gait groups because the maximum muscle forces of the muscles related to balance and stability (e.g., glut med, glut min, tfl, vas int, extobl) of healthy gait group were significantly different to those of affected-limb gait groups. This accords with the previous research that showed the muscle strength of hip abductor muscles (glut med, glut min, tfl) of hip OA patients are smaller than those of healthy subjects [95]. Among the affected-limb gait groups, group D was the most different from other groups with large maximum muscle force for the thigh muscles related to stability. This implies that group D tends to over-activate muscles during gait.

Also, the connection between the latent features of the force plate measurements and the maximum muscle forces of similarity-based groups can be explained by comparing healthy gait and affected-gait groups. Group D was the only group that showed significantly larger muscle forces than the healthy gait group. The muscles were the hamstring muscles (e.g., semimem, semiten, bifemlh) related to the gait stability. For the latent features of the force plate measurements, group D was the only group that showed a larger maximum spatial component score than that of the healthy gait group. Group A was the group that was the most similar to healthy gait but showed a significant difference in the hip, thigh, and trunk muscles related to balance and stability. For the spatial component scores, the magnitude of the scores of group A for the variables related to medial-lateral directions (GRF x and moment y) are slightly

smaller than those of the healthy gait group. Group B showed significant differences in more muscles related to balance and stability than group A and the magnitude of the muscle forces were smaller than those of healthy gait and group A. For the spatial component scores, except for group C that lacked the number of gait trials necessary for meaningful comparison with the healthy gait group, group B had the smallest magnitude of the spatial component scores for the variables related to medial-lateral directions (GRF x and moment y). The connection between the muscle forces related to balance and stability and the spatial component scores of the variables related to the medial-lateral direction is reasonable since the abductor muscles (glut med, glut min, tfl) and hamstrings (semimem, semiten, bifemlh) are known to generate lateral ground reaction forces [96].

From the comparison of the maximum muscle forces during stance of each spatial component-based group shown in table 7 and table 8, it is shown that for the healthy spatial component-based groups, which are the Gaussians of the spatial GMM of healthy gait, there was no significant difference in muscle forces except for the comparison between healthy Gaussian 1 and healthy Gaussian 2,3 which showed a significant difference in the trunk muscle (extobl). For the affected-limb spatial component-based groups, which are the Gaussians of the spatial GMM of affected-limb gait, Gaussian 3 and Gaussian 5 showed a significant difference in muscle force with Gaussian 1 for several common muscles (e.g., semimem, semiten, add brev, add mag, pect, grac, tib post). Among the healthy and affected-limb spatial component-based groups, healthy Gaussian 1 commonly showed significant differences with affected-limb Gaussian 3, 4, 5 in hip and trunk muscle forces (e.g., glut med, extobl). Healthy Gaussian 3 showed a significant difference in shoulder muscle force (pect) with affected-limb Gaussian 1 and trunk muscle force (extobl) with affected-limb Gaussian 3. Healthy Gaussian 5 commonly showed significant differences with affected-limb Gaussian 3 and Gaussian 5 in trunk and ankle muscle forces (e.g., extobl, ext hal).

The connection between the latent features of the force plate measurements and each spatial component-based group's maximum muscle forces can be explained from the comparison between healthy gait group and affected-gait groups. Healthy Gaussian 1 commonly showed significant differences with affected-limb Gaussian 3 and 5 in muscle forces of hip abductor and trunk muscles (glut med, extobl). On the other hand, healthy Gaussian 5 commonly showed significant differences with affected-limb Gaussian 3 and 5 in trunk and ankle muscles (ext hal, extobl). The abduction of the hip abductor muscle (glut med) is related to the movement in the medial-lateral direction, while the extension of the ankle muscle (ext hal) is related to the movement in the anterior-posterior direction. This implies that healthy Gaussian 1 and Gaussian 5 are different in the direction of muscle movements. For the latent features of the force plate measurements, the Gaussian center positions of healthy Gaussian 1 and Gaussian 5 are different in the variables related to anterior-posterior movement (moment x, GRF y). This implies that the Gaussian center positions of each spatial component-based groups are related to the muscle movements' direction.

Therefore, it is shown that the physical meanings or implications of the different types of affected-limb gait, which are identified from the latent features of force plate measurements, can be explained using muscle forces of each group. The muscle force differences between groups explain the distinct characteristics of the groups. Also, it is shown that the muscle force features of each group are related with the latent features of the force plate measurements. Spatial component scores of similarity-based groups reflect the magnitude of the maximum muscle forces and the Gaussian center positions of the spatial component-based groups reflect the direction of the muscle movements.

4.2.2 Muscle forces of the gait types in temporal aspect

From the comparison of the maximum muscle forces of each similarity-based group and temporal component-based group for each stance phase shown in table 9, table 10, table 11, and table 12, the number of muscles that showed significant difference between different groups in each stance phase were calculated to find out the phase characteristics that are distinguishable between groups. The results are shown in table 15 and table 16.

For the similarity-based groups, the phase with the largest and second-largest number of muscles that showed a significant difference between groups was different for all affected-limb groups. For the temporal component-based groups, the number of muscles that showed a significant difference between the two affected-limb groups was the largest at the heel contact phase. This implies that the two affected-limb groups are the most different in the early stance phase in the temporal aspect. There were no significant differences in muscle forces between two healthy groups for all stance phases, which implies that there is no significant difference in healthy groups in the temporal aspect. For the comparison between healthy groups and affected-limb groups, affected-limb Gaussian 1 showed the largest and second-largest number of muscles that showed significant difference with two healthy Gaussians in the heel contact and foot flat phase. Affected-limb Gaussian 2 showed the largest and second-largest number of muscles that showed significant difference with two healthy Gaussians in the foot flat and heel off phase. This implies that the temporal features of each affected-limb Gaussians are consistent regardless of which healthy Gaussian was used for comparison. Also, it can be assumed that the difference between the muscle forces of healthy gait and affected-limb gait is mainly shown in foot flat phase. The reason why this point was not visible in the similarity-based groups is assumed to be because the similarity-based method more specifically divided the gait trials into a larger number of groups than the temporal component-based method. This is related to the previous research results that showed the gluteal muscle forces of patients with hip OA are different to those of healthy subjects in the early part of stance (0% $\sim$ 30% stance) [97].

The temporal characteristics of the muscle forces are reflected in the Gaussian center positions of the temporal component-based groups. From Fig. 9, it is shown that the phase with the largest center

	Heel contact	Foot flat	Mid-stance	Heel off	Toe off
Healthy vs Group A	32	26	13	20	4
Healthy vs Group B	8	10	11	12	0
Healthy vs Group C	10	10	0	4	0
Healthy vs Group D	0	2	29	19	11
Group A vs Group B	2	1	1	2	0
Group A vs Group C	1	4	0	0	0
Group A vs Group D	21	4	20	10	7
Group B vs Group C	1	4	1	0	0
Group B vs Group D	8	6	18	14	12
Group C vs Group D	9	3	10	10	8

Table 15: The number of muscles that showed a significant difference (p-value ≤ 0.05) between healthy groups and affected-limb groups of the similarity-based method.

	Heel contact	Foot flat	Mid-stance	Heel off	Toe off
HG 1 vs AG 1	31	19	12	18	3
HG 1 vs AG 2	7	17	15	18	6
HG 2 vs AG 1	25	16	9	13	1
HG 2 vs AG 2	5	14	8	12	1
HG 1 vs HG 2	0	0	0	0	0
AG 1 vs AG 2	6	1	0	0	0

Table 16: The number of muscles that showed a significant difference (p-value ≤ 0.05) between healthy groups and affected-limb groups of the temporal component-based method. HG stands for Gaussians of healthy gait and AG stands for Gaussians of the gait of hip OA patients.

position difference between healthy gait and affected-limb gait is approximately 15% $\sim$ 30% stance, which accords with the results of the previous research and the important stance phase derived from table 15 and table 16.

Therefore, it is shown that the physical meanings or implications of the different types of affected-limb gait, which were identified from the latent features of force plate measurements, can be explained using muscle forces. It is also shown that the characteristics of each group's muscle forces are related to the latent features of the force plate measurements. The Gaussian center positions of the temporal component-based groups reflect the phase where the difference between healthy gait and affected-limb gait is large. Also, in the temporal component-based groups, which are less specifically divided than the similarity-based groups, it is shown that the phase that showed significant muscle force difference between healthy gait and affected-limb gait correspond to the results of the previous studies.

4.3 Comparison of gait type classification methods

Using the similarity-based method, each gait trial's temporal and spatial gait features can be visualized in one plot, which enables an intuitive understanding and evaluation of each gait trial. Moreover, the grouping validity of the similarity-based method is better than the grouping validity of the component-based method as in table 17. The table shows the silhouette scores of all groups and silhouette scores of individual groups of the similarity-based and component-based groups. The silhouette scores of individual groups are shown in the alphabetical order (group A, group B, group C, group D) for the similarity-

	Silhouette score (of all groups)	Silhouette score (per groups)
Similarity-based method	0.55	0.55, 0.31, 0.53, 0.74
Spatial component-based method (healthy gait)	0.45	0.44, 0.6, 0.4, 0.32, 0.01
Spatial component-based method (affected-limb gait)	0.38	0.51, 0.3, 0.34, 0.63, 0.01
Temporal component-based method (healthy gait)	0.42	0.43, 0.41
Temporal component-based method (affected-limb gait)	0.41	0.48, 0.28

Table 17: The silhouette scores of the similarity-based groups and component-based groups.

based method and the numerical order (Gaussian 1, Gaussian 2, Gaussian 3, Gaussian 4, Gaussian 5) for the component-based method. The similarity-based groups have the largest silhouette score of all groups compared to the component-based groups, which means that the similarity-based method yields better gait groups than the component-based method. This is assumed to be because the similarity-based method groups the gait trials using only temporal and spatial similarity means, while the component-based method groups the gait trials using the entire values of the temporal and spatial components. Therefore, the dimension of the data for clustering is smaller in the similarity-based method, which can lead to better grouping validity. Moreover, the silhouette scores per group of the similarity-based method are relatively uniform compared to those of the spatial component-based method. The silhouette score of the last group of the spatial component-based method of both healthy and affected-limb gait is 0.01, which means that the group overlaps with other groups. On the other hand, the similarity-based groups do not overlap with other groups. However, one limitation of the similarity-based method is that the similarity means might not be reliable in other diseases where several pathological gait types share an equal or similar dominance. Also, the similarity-based method cannot distinguish different types of healthy gait as the component-based method because the similarity-based method divides gait trials into different groups based on the overall similarity of each gait trial to healthy gait. This also makes it difficult to point out the section of the difference of gait trials.

On the other hand, the component-based method can more specifically differentiate and identify different gait types than the similarity-based method. Moreover, due to the characteristics of the mixture modeling, the membership of each gait trial to different gait types can be quantitatively explained using the component-based method. This would be helpful in understanding and quantifying the change in gait of patients under treatment and rehabilitation. However, the number of the identified gait types of the component-based method can be too many for intuitive visualization and understanding. The number of healthy gait groups and the number of affected-limb gait groups was 5, respectively, making it harder to visualize and understand than the similarity-based method. Also, the silhouette scores of the component-based groups, which indicate the grouping validity, are lower than those of the similarity-based groups.

V Conclusion

In conclusion, this paper proposes and compares two approaches (the similarity-based approach and the component-based approach) that can distinguish different types of the gait of patients with hip OA quantitatively using machine learning techniques.

The similarity-based method uses the similarities of the latent features of gait derived from PCA to identify different gait types, while the component-based method uses GMM on the latent features of gait to identify different gait types. The similarity-based method is a more intuitive and simple gait classification method with higher grouping validity that does not require additional clustering methods, unlike the component-based method. On the other hand, the component-based method yields detailed gait groups by considering all spatial and temporal gait features, unlike the similarity-based method.

The physical interpretations of the classified groups are explained using muscle forces estimated with OpenSim. It is shown that the characteristics of the different gait groups identified from the latent features of force plate measurements can be explained using the muscle forces of the groups. It is also shown that the muscle force characteristics are related to the latent features of the force plate measurements.

The approaches will be useful in understanding the gait patterns of patients with hip OA. Also, the proposed gait classification method's overall process can be applied to understand different types of human motion other than the gait of patients with hip OA.

References

[1] M. Constantinou, A. Loureiro, C. Carty, P. Mills, and R. Barrett, "Hip joint mechanics during walking in individuals with mild-to-moderate hip osteoarthritis," *Gait & posture*, vol. 53, pp. 162–167, 2017.

[2] E. M. Bartels, C. B. Juhl, R. Christensen, K. B. Hagen, B. Danneskiold-Samsøe, H. Dagfinrud, and H. Lund, "Aquatic exercise for the treatment of knee and hip osteoarthritis," *Cochrane Database of Systematic Reviews*, no. 3, 2016.

[3] Z. Bejek, R. Paroczai, Á. Illyés, and R. M. Kiss, "The influence of walking speed on gait parameters in healthy people and in patients with osteoarthritis," *Knee surgery, sports traumatology, arthroscopy*, vol. 14, no. 7, pp. 612–622, 2006.

[4] D. D. Dunlop, J. Song, P. A. Semanik, L. Sharma, and R. W. Chang, "Physical activity levels and functional performance in the osteoarthritis initiative: a graded relationship," *Arthritis & Rheumatism*, vol. 63, no. 1, pp. 127–136, 2011.

[5] A. R. Anwary, H. Yu, and M. Vassallo, "Gait evaluation using procrustes and euclidean distance matrix analysis," *IEEE journal of biomedical and health informatics*, vol. 23, no. 5, pp. 2021–2029, 2018.

[6] J. Klucken, J. Barth, P. Kugler, J. Schlachetzki, T. Henze, F. Marxreiter, Z. Kohl, R. Steidl, J. Hornegger, B. Eskofier, *et al.*, "Unbiased and mobile gait analysis detects motor impairment in parkinson's disease," *PloS one*, vol. 8, no. 2, p. e56956, 2013.

[7] R. J. Leigh, S. T. Osis, and R. Ferber, "Kinematic gait patterns and their relationship to pain in mild-to-moderate hip osteoarthritis," *Clinical Biomechanics*, vol. 34, pp. 12–17, 2016.

[8] L. Wang, Y. Sun, Q. Li, T. Liu, and J. Yi, "Imu-based gait normalcy index calculation for clinical evaluation of impaired gait," *IEEE Journal of Biomedical and Health Informatics*, 2020.

[9] Z.-Q. Zhang, L.-Y. Ji, Z.-P. Huang, and J.-K. Wu, "Adaptive information fusion for human upper limb movement estimation," *IEEE Transactions on systems, man, and cybernetics-part A: systems and humans*, vol. 42, no. 5, pp. 1100–1108, 2012.

[10] P. Ornetti, D. Laroche, C. Morisset, J. N. Beis, C. Tavernier, and J.-F. Maillefert, "Three-dimensional kinematics of the lower limbs in hip osteoarthritis during walking," *Journal of back and musculoskeletal rehabilitation*, vol. 24, no. 4, pp. 201–208, 2011.

[11] M. Peterson, P. Kovar-Toledano, J. Otis, J. Allegrante, C. Mackenzie, B. Gutin, and M. Kroll, "Effect of a walking program on gait characteristics in patients with osteoarthritis," *Arthritis &*

Rheumatism: Official Journal of the American College of Rheumatology, vol. 6, no. 1, pp. 11–16, 1993.

[12] D. Bennett, P. Ryan, S. O'Brien, and D. E. Beverland, "Gait kinetics of total hip replacement patients—a large scale, long-term follow-up study," *Gait & posture*, vol. 53, pp. 173–178, 2017.

[13] M. Hall, S. Chabra, N. Shakoor, S. E. Leurgans, H. Demirtas, and K. C. Foucher, "Hip joint moments in symptomatic vs. asymptomatic people with mild radiographic hip osteoarthritis," *Journal of Biomechanics*, vol. 96, p. 109347, 2019.

[14] J. L. McCrory, S. C. White, and R. M. Lifeso, "Vertical ground reaction forces: objective measures of gait following hip arthroplasty," *Gait & posture*, vol. 14, no. 2, pp. 104–109, 2001.

[15] M. H. Arokoski, J. P. Arokoski, M. Haara, M. Kankaanpää, M. Vesterinen, L. H. Niemitukia, and H. J. Helminen, "Hip muscle strength and muscle cross sectional area in men with and without hip osteoarthritis.," *The Journal of rheumatology*, vol. 29, no. 10, pp. 2185–2195, 2002.

[16] D. J. Rutherford, J. Moreside, and I. Wong, "Hip joint motion and gluteal muscle activation differences between healthy controls and those with varying degrees of hip osteoarthritis during walking," *Journal of Electromyography and Kinesiology*, vol. 25, no. 6, pp. 944–950, 2015.

[17] D. A. Neumann, D. C. Sobush, S. Paschke, and T. M. Cook, "An electromyographic analysis of the hip abductor muscles during a standing work task," *Arthritis & Rheumatism: Official Journal of the American College of Rheumatology*, vol. 3, no. 3, pp. 116–126, 1990.

[18] J.-H. Yoo, M. S. Nixon, and C. J. Harris, "Model-driven statistical analysis of human gait motion," in *Proceedings. International Conference on Image Processing*, vol. 1, pp. I–I, IEEE, 2002.

[19] D. Slijepcevic, M. Zeppelzauer, A.-M. Gorgas, C. Schwab, M. Schüller, A. Baca, C. Breiteneder, and B. Horsak, "Automatic classification of functional gait disorders," *IEEE journal of biomedical and health informatics*, vol. 22, no. 5, pp. 1653–1661, 2017.

[20] W. Wang, D. C. Ackland, J. A. McClelland, K. E. Webster, and S. Halgamuge, "Assessment of gait characteristics in total knee arthroplasty patients using a hierarchical partial least squares method," *IEEE journal of biomedical and health informatics*, vol. 22, no. 1, pp. 205–214, 2017.

[21] F. Wahid, R. K. Begg, C. J. Hass, S. Halgamuge, and D. C. Ackland, "Classification of parkinson's disease gait using spatial-temporal gait features," *IEEE journal of biomedical and health informatics*, vol. 19, no. 6, pp. 1794–1802, 2015.

[22] K. Deluzio and J. Astephen, "Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis," *Gait & posture*, vol. 25, no. 1, pp. 86–93, 2007.

[23] M. A. Motin, C. K. Karmakar, and M. Palaniswami, "Ensemble empirical mode decomposition with principal component analysis: A novel approach for extracting respiratory rate and heart rate from photoplethysmographic signal," *IEEE journal of biomedical and health informatics*, vol. 22, no. 3, pp. 766–774, 2017.

[24] M. Wu, Y.-L. Gao, J.-X. Liu, C.-H. Zheng, and J.-W. Wang, "Integrative hypergraph regularized principal component analysis for sample clustering and co-expression genes network analysis on multi-omics data," *IEEE Journal of Biomedical and Health Informatics*, 2019.

[25] G. R. Naik and H. T. Nguyen, "Nonnegative matrix factorization for the identification of emg finger movements: Evaluation using matrix analysis," *IEEE journal of biomedical and health informatics*, vol. 19, no. 2, pp. 478–485, 2014.

[26] M. Cross, F. Guillemin, W. Ngueyon, and L. March, "Validation of lay descriptions of levels of severity of knee and hip oa in the khoala cohort study," *Osteoarthritis and Cartilage*, vol. 24, p. S204, 2016.

[27] E. Dolatabadi, A. Mansfield, K. K. Patterson, B. Taati, and A. Mihailidis, "Mixture-model clustering of pathological gait patterns," *IEEE journal of biomedical and health informatics*, vol. 21, no. 5, pp. 1297–1305, 2016.

[28] C. H. Roux, A. Saraux, B. Mazieres, J. Pouchot, J. Morvan, B. Fautrel, J. Testa, P. Fardellone, A. C. Rat, J. Coste, *et al.*, "Screening for hip and knee osteoarthritis in the general population: predictive value of a questionnaire and prevalence estimates," *Annals of the rheumatic diseases*, vol. 67, no. 10, pp. 1406–1411, 2008.

[29] J. Damen, R. M. van Rijn, P. J. Emans, W. K. Hilberdink, J. Wesseling, E. H. Oei, and S. M. Bierma-Zeinstra, "Prevalence and development of hip and knee osteoarthritis according to american college of rheumatology criteria in the check cohort," *Arthritis research & therapy*, vol. 21, no. 1, p. 4, 2019.

[30] R. Hirsch, R. J. Fernandes, S. R. Pillemer, M. C. Hochberg, N. E. Lane, R. D. Altman, D. A. Bloch, W. C. Knowler, and P. H. Bennett, "Hip osteoarthritis prevalence estimates by three radiographic scoring systems," *Arthritis & Rheumatism: Official Journal of the American College of Rheumatology*, vol. 41, no. 2, pp. 361–368, 1998.

[31] S. Chen, J. Lach, B. Lo, and G.-Z. Yang, "Toward pervasive gait analysis with wearable sensors: A systematic review," *IEEE journal of biomedical and health informatics*, vol. 20, no. 6, pp. 1521–1537, 2016.

[32] J. Perry, J. R. Davids, *et al.*, "Gait analysis: normal and pathological function," *Journal of Pediatric Orthopaedics*, vol. 12, no. 6, p. 815, 1992.

[33] B. Mariani, H. Rouhani, X. Crevoisier, and K. Aminian, "Quantitative estimation of foot-flat and stance phase of gait using foot-worn inertial sensors," *Gait & posture*, vol. 37, no. 2, pp. 229–234, 2013.

[34] M. Alaqtash, T. Sarkodie-Gyan, H. Yu, O. Fuentes, R. Brower, and A. Abdelgawad, "Automatic classification of pathological gait patterns using ground reaction forces and machine learning algorithms," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 453–457, IEEE, 2011.

[35] H. H. Manap, N. M. Tahir, and A. I. M. Yassin, "Statistical analysis of parkinson disease gait classification using artificial neural network," in *2011 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, pp. 060–065, IEEE, 2011.

[36] D. Slijepcevic, M. Zeppelzauer, C. Schwab, A.-M. Raberger, C. Breiteneder, and B. Horsak, "Input representations and classification strategies for automated human gait analysis," *Gait & Posture*, vol. 76, pp. 198–203, 2020.

[37] K. Allab, L. Labiod, and M. Nadif, "Simultaneous semi-nmf and pca for clustering," in *2015 IEEE International Conference on Data Mining*, pp. 679–684, IEEE, 2015.

[38] A. Muniz and J. Nadal, "Application of principal component analysis in vertical ground reaction force to discriminate normal and abnormal gait," *Gait & posture*, vol. 29, no. 1, pp. 31–35, 2009.

[39] F. Demrozi, R. Bacchin, S. Tamburin, M. Cristani, and G. Pravadelli, "Towards a wearable system for predicting the freezing of gait in people affected by parkinson's disease," *IEEE journal of biomedical and health informatics*, 2019.

[40] A. A. Khan, D. Iliescu, R. J. Sneath, C. E. Hutchinson, and A. Shah, "Principal component and factor analysis to study variations in the aging lumbar spine," *IEEE journal of biomedical and health informatics*, vol. 19, no. 2, pp. 745–751, 2014.

[41] W. Liu, K. Yuan, and D. Ye, "Reducing microarray data via nonnegative matrix factorization for visualization and clustering analysis," *Journal of biomedical informatics*, vol. 41, no. 4, pp. 602–606, 2008.

[42] D. D. Lee and H. S. Seung, "Algorithms for non-negative matrix factorization," in *Advances in neural information processing systems*, pp. 556–562, 2001.

[43] F. Shahnaz, M. W. Berry, V. P. Pauca, and R. J. Plemmons, "Document clustering using nonnegative matrix factorization," *Information Processing & Management*, vol. 42, no. 2, pp. 373–386, 2006.

[44] S. Mika, B. Schölkopf, A. J. Smola, K.-R. Müller, M. Scholz, and G. Rätsch, "Kernel pca and de-noising in feature spaces," in *Advances in neural information processing systems*, pp. 536–542, 1999.

[45] H. Hoffmann, "Kernel pca for novelty detection," *Pattern recognition*, vol. 40, no. 3, pp. 863–874, 2007.

[46] T. Chen, E. Martin, and G. Montague, "Robust probabilistic pca with missing data and contribution analysis for outlier detection," *Computational Statistics & Data Analysis*, vol. 53, no. 10, pp. 3706–3716, 2009.

[47] C. M. Bishop, M. Svensén, and C. K. Williams, "Gtm: The generative topographic mapping," *Neural computation*, vol. 10, no. 1, pp. 215–234, 1998.

[48] J. M. Wang, D. J. Fleet, and A. Hertzmann, "Gaussian process dynamical models for human motion," *IEEE transactions on pattern analysis and machine intelligence*, vol. 30, no. 2, pp. 283–298, 2007.

[49] N. Lawrence, "Probabilistic non-linear principal component analysis with gaussian process latent variable models," *Journal of machine learning research*, vol. 6, no. Nov, pp. 1783–1816, 2005.

[50] P. Praus, "Water quality assessment using svd-based principal component analysis of hydrological data," *Water SA*, vol. 31, no. 4, pp. 417–422, 2005.

[51] D. Owaki, K. Honda, Y. Sekiguchi, and S.-i. Izumi, "Principal component analysis for whole body angular momentum during walking in patients with stroke," *IFAC-PapersOnLine*, 2019.

[52] D. Rutherford, L. Buckingham, J. Moreside, I. Wong, and G. Richardson, "Knee motion and muscle activation patterns are altered in hip osteoarthritis: The effect of severity on walking mechanics," *Clinical Biomechanics*, vol. 59, pp. 1–7, 2018.

[53] K. Wagstaff, C. Cardie, S. Rogers, S. Schrödl, *et al.*, "Constrained k-means clustering with background knowledge," in *Icml*, vol. 1, pp. 577–584, 2001.

[54] A. Likas, N. Vlassis, and J. J. Verbeek, "The global k-means clustering algorithm," *Pattern recognition*, vol. 36, no. 2, pp. 451–461, 2003.

[55] P. A. Burrough, P. F. van Gaans, and R. MacMillan, "High-resolution landform classification using fuzzy k-means," *Fuzzy sets and systems*, vol. 113, no. 1, pp. 37–52, 2000.

[56] R. Li, Z. Wang, C. Gu, F. Li, and H. Wu, "A novel time-of-use tariff design based on gaussian mixture model," *Applied energy*, vol. 162, pp. 1530–1536, 2016.

[57] F. Wang, H.-H. Franco-Penya, J. D. Kelleher, J. Pugh, and R. Ross, "An analysis of the application of simplified silhouette to the evaluation of k-means clustering validity," in *International Conference on Machine Learning and Data Mining in Pattern Recognition*, pp. 291–305, Springer, 2017.

[58] D. L. Davies and D. W. Bouldin, "A cluster separation measure," *IEEE transactions on pattern analysis and machine intelligence*, no. 2, pp. 224–227, 1979.

[59] P. J. Rousseeuw, "Silhouettes: a graphical aid to the interpretation and validation of cluster analysis," *Journal of computational and applied mathematics*, vol. 20, pp. 53–65, 1987.

[60] F. Schellenberg, K. Oberhofer, W. R. Taylor, and S. Lorenzetti, "Review of modelling techniques for in vivo muscle force estimation in the lower extremities during strength training," *Computational and mathematical methods in medicine*, vol. 2015, 2015.

[61] W. Blajer, A. Czaplicki, K. Dziewiecki, and Z. Mazur, "Influence of selected modeling and computational issues on muscle force estimates," *Multibody System Dynamics*, vol. 24, no. 4, pp. 473–492, 2010.

[62] J. Hashemi, E. Morin, P. Mousavi, and K. Hashtrudi-Zaad, "Enhanced dynamic emg-force estimation through calibration and pci modeling," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 23, no. 1, pp. 41–50, 2014.

[63] G. Johns, E. Morin, and K. Hashtrudi-Zaad, "Force modelling of upper limb biomechanics using ensemble fast orthogonal search on high-density electromyography," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 10, pp. 1041–1050, 2016.

[64] D. K. Kumar, N. D. Pah, and A. Bradley, "Wavelet analysis of surface electromyography," *IEEE Transactions on neural systems and rehabilitation engineering*, vol. 11, no. 4, pp. 400–406, 2003.

[65] J. Langenderfer, S. LaScalza, A. Mell, J. E. Carpenter, J. E. Kuhn, and R. E. Hughes, "An emg-driven model of the upper extremity and estimation of long head biceps force," *Computers in biology and medicine*, vol. 35, no. 1, pp. 25–39, 2005.

[66] S. Sikdar, H. Rangwala, E. B. Eastlake, I. A. Hunt, A. J. Nelson, J. Devanathan, A. Shin, and J. J. Pancrazio, "Novel method for predicting dexterous individual finger movements by imaging

muscle activity using a wearable ultrasonic system," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 1, pp. 69–76, 2013.

[67] M. Kim, K. Kim, and W. K. Chung, "Simple and fast compensation of semg interface rotation for robust hand motion recognition," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 12, pp. 2397–2406, 2018.

[68] M. Damsgaard, J. Rasmussen, S. T. Christensen, E. Surma, and M. De Zee, "Analysis of musculoskeletal systems in the anybody modeling system," *Simulation Modelling Practice and Theory*, vol. 14, no. 8, pp. 1100–1111, 2006.

[69] J. Xu, Y. Li, L. Xu, C. Peng, S. Chen, J. Liu, C. Xu, G. Cheng, H. Xu, Y. Liu, *et al.*, "A multi-mode rehabilitation robot with magnetorheological actuators based on human motion intention estimation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 27, no. 10, pp. 2216–2228, 2019.

[70] F. Mo, H. Zhang, L. Wang, M. Behr, and P. J. Arnoux, "A framework of a lower limb musculoskeletal model with implemented natural proprioceptive feedback and its progressive evaluation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2020.

[71] C. Pizzolato, M. Reggiani, D. J. Saxby, E. Ceseracciu, L. Modenese, and D. G. Lloyd, "Biofeedback for gait retraining based on real-time estimation of tibiofemoral joint contact forces," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 9, pp. 1612–1621, 2017.

[72] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen, "Opensim: open-source software to create and analyze dynamic simulations of movement," *IEEE transactions on biomedical engineering*, vol. 54, no. 11, pp. 1940–1950, 2007.

[73] A. Seth, M. Sherman, J. A. Reinbolt, and S. L. Delp, "Opensim: a musculoskeletal modeling and simulation framework for in silico investigations and exchange," *Procedia Iutam*, vol. 2, pp. 212–232, 2011.

[74] J. Ueda, D. Ming, V. Krishnamoorthy, M. Shinohara, and T. Ogasawara, "Individual muscle control using an exoskeleton robot for muscle function testing," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 4, pp. 339–350, 2010.

[75] S. Heintz and E. M. Gutierrez-Farewik, "Static optimization of muscle forces during gait in comparison to emg-to-force processing approach," *Gait & posture*, vol. 26, no. 2, pp. 279–288, 2007.

[76] D. Davy and M. Audu, "A dynamic optimization technique for predicting muscle forces in the swing phase of gait," *Journal of biomechanics*, vol. 20, no. 2, pp. 187–201, 1987.

[77] F. C. van der Helm and H. Veeger, "Quasi-static analysis of muscle forces in the shoulder mechanism during wheelchair propulsion," *Journal of Biomechanics*, vol. 29, no. 1, pp. 39–52, 1996.

[78] R. Bogey, J. Perry, and A. Gitter, "An emg-to-force processing approach for determining ankle muscle forces during normal human gait," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 13, no. 3, pp. 302–310, 2005.

[79] D. G. Thelen, F. C. Anderson, and S. L. Delp, "Generating dynamic simulations of movement using computed muscle control," *Journal of biomechanics*, vol. 36, no. 3, pp. 321–328, 2003.

[80] D. G. Thelen and F. C. Anderson, "Using computed muscle control to generate forward dynamic simulations of human walking from experimental data," *Journal of biomechanics*, vol. 39, no. 6, pp. 1107–1115, 2006.

[81] K. Endo and H. Herr, "A model of muscle–tendon function in human walking at self-selected speed," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 2, pp. 352–362, 2013.

[82] A. Erdemir, S. McLean, W. Herzog, and A. J. van den Bogert, "Model-based estimation of muscle forces exerted during movements," *Clinical biomechanics*, vol. 22, no. 2, pp. 131–154, 2007.

[83] R. Rasnick, T. Standifird, J. A. Reinbolt, H. E. Cates, and S. Zhang, "Knee joint loads and surrounding muscle forces during stair ascent in patients with total knee replacement," *PloS one*, vol. 11, no. 6, p. e0156282, 2016.

[84] O. Skalshøi, C. H. Iversen, D. B. Nielsen, J. Jacobsen, I. Mechlenburg, K. Søballe, and H. Sørensen, "Walking patterns and hip contact forces in patients with hip dysplasia," *Gait & posture*, vol. 42, no. 4, pp. 529–533, 2015.

[85] H. Kainz, L. Modenese, D. Lloyd, S. Maine, H. Walsh, and C. Carty, "Joint kinematic calculation based on clinical direct kinematic versus inverse kinematic gait models," *Journal of biomechanics*, vol. 49, no. 9, pp. 1658–1669, 2016.

[86] I. T. Jolliffe and J. Cadima, "Principal component analysis: a review and recent developments," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374, no. 2065, p. 20150202, 2016.

[87] N. P. P. Macciotta, G. Gaspa, R. Steri, E. L. Nicolazzi, C. Dimauro, C. Pieramati, and A. Cappio-Borlino, "Using eigenvalues as variance priors in the prediction of genomic breeding values by principal component analysis," *Journal of dairy science*, vol. 93, no. 6, pp. 2765–2774, 2010.

[88] I. Jonkers, C. Stewart, and A. Spaepen, "The complementary role of the plantarflexors, hamstrings and gluteus maximus in the control of stance limb stability during gait," *Gait & posture*, vol. 17, no. 3, pp. 264–272, 2003.

[89] Ö. Özkal, M. Kara, S. Topuz, B. Kaymak, A. Bakı, and L. Özçakar, "Assessment of core and lower limb muscles for static/dynamic balance in the older people: An ultrasonographic study," *Age and ageing*, vol. 48, no. 6, pp. 881–887, 2019.

[90] F. Gottschalk, S. Kourosh, and B. Leveau, "The functional anatomy of tensor fasciae latae and gluteus medius and minimus.," *Journal of anatomy*, vol. 166, p. 179, 1989.

[91] J. W. Youdas, J. W. Hubble, P. G. Johnson, M. M. McCarthy, M. M. Saenz, and J. H. Hollman, "Scapular muscle balance and spinal stabilizer recruitment during an inverted row," *Physiotherapy theory and practice*, vol. 36, no. 3, pp. 432–443, 2020.

[92] I. Cikajlo, A. Krpič, and M. Gorišek-Humar, "Changes in emg latencies during balance therapy using enhanced virtual reality with haptic floor," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 4129–4132, IEEE, 2013.

[93] D. Rhodes, J. Jeffrey, J. Maden-Wilkinson, A. Reedy, E. Morehead, J. Kiely, D. Birdsall, C. Carling, and J. Alexander, "The relationship between eccentric hamstring strength and dynamic stability in elite academy footballers.," *Science and Medicine in Football*, 2020.

[94] O. Caron, "Effects of local fatigue of the lower limbs on postural control and postural stability in standing posture," *Neuroscience letters*, vol. 340, no. 2, pp. 83–86, 2003.

[95] A. Loureiro, P. M. Mills, and R. S. Barrett, "Muscle weakness in hip osteoarthritis: a systematic review," *Arthritis care & research*, vol. 65, no. 3, pp. 340–352, 2013.

[96] C. T. John, A. Seth, M. H. Schwartz, and S. L. Delp, "Contributions of muscles to mediolateral ground reaction force over a range of walking speeds," *Journal of biomechanics*, vol. 45, no. 14, pp. 2438–2443, 2012.

[97] A. Zacharias, T. Pizzari, A. I. Semciw, D. J. English, T. Kapakoulakis, and R. A. Green, "Comparison of gluteus medius and minimus activity during gait in people with hip osteoarthritis and matched controls," *Scandinavian journal of medicine & science in sports*, vol. 29, no. 5, pp. 696–705, 2019.

요 약 문

주성분 분석(Principal Component Analysis)과 가우시안 혼합 모델(Gaussian Mixture Model)을 이용한 고관절 퇴행성 관절염 환자들의 보행 분류

고관절 퇴행성 관절염은 고관절의 관절연골이 닳으면서 관절 안에 염증이 생기는 질환이다. 이 질환에 대한 기존의 진단 방법들은 주로 설문지 등의 정성적인 방법을 이용하며 환자들을 단순히 질환의 경중으로 분류를 한다는 문제점이 있다. 또한 이 질환은 환자들의 움직임에 영향을 끼치기 때문에 이 질환의 특징을 파악하기 위해 환자들의 보행을 분석하는 연구들이 진행되었는데 대부분의 연구에서 여러 보행 측정값들을 따로 평가하기 때문에 종합적인 보행의 평가와 진단이 부족하다는 문제가 있다. 또한, 보행 시 근력 등의 데이터를 얻기 위해 센서를 사용하는데 이는 사람들의 자연스러운 움직임을 방해할 수 있다는 한계점이 있다. 따라서 이 연구는 센서를 사용하지 않고 힘판과 머신러닝 기법들을 사용하여 고관절 퇴행성 관절염 환자들의 보행을 정량적으로 분류하고 평가할 수 있는 두 가지 방법론을 제시한다.

총 22명의 고관절 퇴행성 관절염 환자들과 18명의 건강한 사람들을 대상으로 보행 시 지면 반력과 모멘트를 측정하였다. 측정된 데이터의 핵심적인 특징을 확인하기 위해 주성분 분석을 사용하여 데이터의 내제된 핵심 보행 특징을 추출하였다. 보행 데이터에서 시간의 흐름에 따른 핵심 보행 특징과 시간에 독립적인 핵심 보행 특징을 추출할 수 있으며, 이 핵심 보행 특징들은 원래 데이터들의 분포에 따른 선형결합으로 이루어지기 때문에 전체 측정값들을 혼합한 새로운 특징이 된다.

보행을 분류하는 첫 번째 방법은 각 보행의 핵심 보행 특징들의 유사도를 측정하는 것이다. 핵심 보행 특징들의 유사도는 각 보행이 서로 얼만큼 유사한지 알려주는 척도가 된다. 건강한 사람들의 보행과 고관절 퇴행성 관절염 환자들의 보행 사이의 유사도를 평가하고, 건강한 사람들의 보행과의 유사도를 기준으로 고관절 퇴행성 관절염 환자들의 보행을 총 4가지로 분류하였다. 분류된 각 보행 그룹의 특징은 각 그룹의 유사도 값과 주성분 분석을 통해 줄어든 차원에서의 힘판 측정값을 통해 설명 가능하다.

보행을 분류하는 두 번째 방법은 각 보행의 핵심 보행 특징 값을 가우시안 혼합 모델을 이용하여 군집화 하는 것이다. 가우시안 혼합 모델은 확률 모델을 기반으로 하는 군집화 방법으로, 전

체 보행의 분포를 모델링할 수 있고 이를 확률적으로 제시하여 한 보행이 어떤 군집 또는 보행 그룹에 어느 정도 속해 있는지 정량적으로 설명할 수 있으므로 보행 분류에 적합하다. 가우시안 혼합 모델을 이용하여 보행의 시간에 독립적인 특징을 기반으로 고관절 퇴행성 관절염 환자들의 보행을 총 5가지로 분류하였고 보행의 시간의 흐름에 따른 특징을 기반으로 고관절 퇴행성 관절염 환자들의 보행을 총 2가지로 분류하였다. 분류된 각 보행 그룹의 특징은 각 그룹에 해당하는 가우시안의 중심 값과 그 부호를 이용하여 설명 가능하다.

분류된 보행의 물리적 의미를 보행 시 근육이 발생하는 힘으로 설명하기 위해 OpenSim이라는 근골격계 소프트웨어로 각 보행의 근력을 계산하였으며 보행 그룹별 근육이 발생하는 힘의 전체 보행 주기에서의 최대값과 각 주기 별 최대값의 비교를 통해 각 보행 그룹이 어느 근육 및 어느 보행 주기에서 차이를 보이는지 확인할 수 있었다. 또한, 분류된 보행의 근력과 보행을 분류할 때 사용된 내제된 핵심 보행 특징 사이의 연관성을 확인하였다.

결론적으로, 주성분 분석과 가우시안 혼합 모델을 사용하여 두 가지 방법으로 고관절 퇴행성 관절염 환자들의 보행을 분류할 수 있었다. 첫 번째 방법은 주성분 분석으로 도출한 핵심 보행 특징의 유사도를 이용하는 방법으로 환자들의 보행을 총 4가지로 분류할 수 있으며 각 보행 그룹은 건강한 사람들의 보행과의 전반적인 유사도와 근육이 발생하는 힘에서 서로 다른 특징을 보인다. 두 번째 방법은 핵심 보행 특징을 가우시안 혼합 모델을 이용하여 분류하는 방법으로 환자들의 보행을 시간과 독립적인 특징을 기반으로 총 5가지, 시간의 흐름에 따른 특징을 기반으로 총 2가지로 분류할 수 있으며 각 보행 그룹은 가우시안의 중심 값과 근육이 발생하는 힘에서 서로 다른 특징을 보인다.

위 두 방법론 중 유사도를 이용하는 방법은 주성분 분석을 이용한 데이터의 차원 축소 후 추가적인 군집화 알고리즘을 사용할 필요 없이 보행 분류가 가능하다는 이점이 있으며 분류된 보행 그룹의 유효성이 가우시안 혼합 모델을 사용하는 방법의 보행 그룹보다 더 높았다. 가우시안 혼합 모델을 이용하는 방법은 일반인과의 전반적인 유사도를 가지고 보행을 분류하는 방법과는 다르게 핵심 보행 특징의 모든 값을 고려한 더 세밀한 보행 특징 분류가 가능하다는 이점이 있다. 또한 확률 모델로 보행의 분포를 측정하기 때문에 시간에 따른 보행 변화 등을 추적하기에 적합하다는 장점도 있다.

핵심어: 보행 분류, 주성분 분석, 가우시안 혼합 모델, OpenSim