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Effect of Joint Limitation and Balance Control for Gait Changes in Diabetic Peripheral Neuropathy

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Abstract

Background: Foot ulcers are the most physically disabling chronic complications of diabetes. Prevention and management of foot ulcers are related to the quality of life and prognosis of diabetic patients. The purpose of this study was to analyze the gait patterns of patients with diabetic peripheral neuropathy and changes in their center of mass sway due to peripheral neuropathy to help prevent the formation of foot ulcers and their recurrence after ulcer healing.

Methods: Forty-two subjects with diagnosis of DM consisted of three groups which were DM group (neither neuropathy nor foot ulcer history), DPN group (with neuropathy and without foot ulcer history), and DFU group (with neuropathy and foot ulcer history). We measured range of motion (ROM) of the lower limb joints at resting position and center of mass sway at standing position. By using 3-D gait analysis, lower limb joint angles in each walking phase and ROM during the during walking, distance factors (step length and step width) were evaluated.

Results: Concerning the knee joint of the DFU group, function limitation at rest was not observed but ROM limitation during walking was detected. Both of the function and ROM limitations were found regarding the ankle joint of the DFU group. The step length ratio and the step width in the DFU group were significantly lower and higher than the DM group, respectively. The sway distances in the DFU group were higher than the DM and DPN group.

Conclusions: It is assumed in DFU group that there is a mixture of functional limitation of the joints themselves and changes in gait due to decreased ability to maintain center of gravity. As diabetic peripheral neuropathy progresses, the gait becomes small, wide and shuffle. Because this gait pattern can induce increased planter pressure and shear forces, supporting joint movement during walking will be able to reduce the incidence and recurrence of foot ulcers.

Keywords: Type 2 diabetes mellitus, Foot ulcer, Diabetic neuropathy, Gait analysis, Center of Mass Sway, Balance

Introduction

The prevalence of diabetic foot ulcers in the world is 1.5-10% and the incidence is 2.2-5.9% (1:Abbott et al 1998, 2:Ramsey et al 1999, 3:Abbott et al 2002). Because foot ulcers precede 80-85% of diabetes mellitus (DM)-related lower extremity amputations (4:Frykberg RG et al 2006), preventing and managing foot ulcers is closely related to the quality of life and prognosis of diabetic patients (5:Raspovic 2013). There are two main causes of diabetic foot ulcers, peripheral arterial disease and peripheral neuropathy. It is reported that patients with foot ulcers caused by the peripheral neuropathy are more common than the peripheral arterial disease (6:Moulik PK et al 2003). Because neuropathic foot ulcers are mainly caused by sensory and motor neuropathy which is difficult to be treated, it is very important to suppress ulcer development and prevent recurrence after healing. To prevent the occurrence and recurrence of foot ulcers, footwears and insoles with high decompression performance is reported to be effective, but the recurrence rate of foot ulcers is still as high as 40% (7:Bus SA et al 2013).

In addition to plantar dysesthesia caused by sensory neuropathy, DM patients are known to suffer from muscle atrophy and limited range of motion (ROM) of joints due to glycosylation to proteins and lipids and motor neuropathy (8:Wrobel J et al 2010). It has been pointed out that foot ulcers develop as a result of morphological changes in gait due to the combined effects of these factors (9:Andersen H 2012, 10:Giacomozzi C et al 2005, 11:Mueller MJ et al 1989). Although there have been some studies in which detailed dynamic measurements and analyses of speed, pace, stride length, and pattern about gait have been performed in DM patients, the mechanism of foot ulcer development has not been elucidated (8:Wrobel J et al 2010). Furthermore, effect of body mass sway has been less considered in relation to their gait.

The purpose of this study was to examine how the DM peripheral neuropathy affects gait changes through analyzing joint movement at rest and during walking and evaluating center of mass sway in patients with DM peripheral neuropathy. These analyses will be able to contribute to the elucidation of the pathogenesis of foot ulcers and the probability of preventive strategies.

Methods

1. Study participants

Subjects were recruited from patients diagnosed with DM (type I and type II) at Tokushima University Hospital between September 2017 and May 2019. All participants were classified into three groups which were DM group (neither diabetic peripheral neuropathy nor foot ulcer history) for control, DPN (diabetic peripheral neuropathy) group (with diabetic peripheral neuropathy and without foot ulcer history), and DFU (diabetic foot ulcer) group (with diabetic peripheral neuropathy and foot ulcer history). Exclusion criteria were subjects who require any assisting apparatus to walk, suffer from peripheral arterial disease in which skin perfusion pressure less than 40 mmHg at any one location, and could not give consent for this study. Subjects with two of the symptoms that are loss of Achilles tendon reflex, decreased vibration perception or decreased plantar perception were considered to have diabetic peripheral neuropathy. This study was approved by the Clinical Research Ethics Review Committee of Tokushima University Hospital, and informed consent was obtained for all subjects prior to the study.

2. Range of Motion of Lower Leg at Resting Position (ROM-Rest)

The ROM of the hip joint, knee joint, ankle joint, and metatarsophalangeal (MTP) joint of the first toe were measured at a supine position on a bed. Active and passive ROM for flexion and extension were measured at each joint. We defined Range of Motion at Resting Position (ROM-Rest) as the sum of the ROM for flexion and the ROM for extension of each joint (Table 1).

3. Gait analysis

Nine reference points were set up on the floor at every 1m in length and 0.5m in width on a rectangle floor of 2m in length and 1m in width. Five points were set up at every 0.28m in height vertically from each reference point. Therefore, total of 45 points were placed for the measuring area. The subjects walked on a 2m walking path with a 2m approaching path, wearing sneakers at their own comfortable speed for gait analysis. Their walking was recorded with a video camera (EX-100F CASIO, Japan) at 120 frame per second (fps) from front and side directions. The captured video images were analyzed offline with Frame-DIAS 6 2D version (DKH, Q'sfix, Japan). The gait process was separated into 7 phases and analyzed in these phases which are Loading Response phase, Mid Stance phase, Terminal Stance phase, Pre Swing phase, Initial Swing phase, Mid Swing phase, and Terminal Swing phase (12:Perry J 2010).

Reflective markers were placed on the anterior superior iliac spine, greater trochanter, lateral epicondyle of femoral, lateral malleolus, lateral heel, lateral fifth toe MTP joint, and second toe phalanges. The angles of the hip, knee, ankle, and toe MTP joints were measured by analyzing the lateral-image gait movies. The angle of the hip joint was measured by connecting the three points of the anterior superior iliac spine, the greater trochanter, and the lateral epicondyle of femoral. Similarly, the angles of the knee joint, the ankle joint, the toe MTP joint were measured.

The joint angles measured at the middle of each walking phase were compared among the 3 groups. Then the difference between the maximum and minimum points of each joint angle in a walking cycle was defined as "Range of Motion during walk (ROM-walk)" (Figure 1, Table 1).

The distance between the bilateral heel markers in a walking cycle were measured from the lateral video and defined as step length. The distance between the bilateral heel markers in a walking cycle was measured from the frontal video and defined as step width. Because there was a significant difference in height between the groups, the measurements of the distant factors were divided by each height. Ratio of the step length and step width to each height were calculated (Table 1).

4. Center of Mass Sway at Standing Position

While the subjects were standing on a measuring device (Wii Fit, Nintendo, Japan), movement of their center of mass was recorded. Measurements were performed with eyes open and closed at 2 kinds of foot width of 0 cm and 10 cm. Distance between the center of the device and the recorded center of mass of the subject was measured continuously for 30 seconds. Then the average sway distance was calculated (Table 1).

5. Statistical analysis

IBM SPSS Statistics 25.0 (2017, Stats Guild Inc. Japan) was used to carry out statistical tests. The Kruskal-Wallis test with a significance level of 0.05 was performed on all of the mean values to reveal any differences among the three groups.

Results

1. Study participants

Forty-two subjects (man /woman: 25 /17, mean age ± SD: 58.9 ± 14.8 years) participated in the study (Table 2). Among the three groups, age, weight, and BMI were not significantly different by Kruskal-Wallis test. The height in the DFU group was significantly higher than it in the DM group, because all participants in the DFU group were men.

2. ROM at Resting Position (ROM-Rest)

As the diabetic peripheral neuropathy progress, tendency of decrease in ROM-Rest of each joint was observed among the 3 groups (Figure 2). There was no significant difference in the ROM-Rest for both the hip and knee joints. In the ankle joint, both of the active and passive ROM-Rest of the DFU group were significantly smaller than these of the DM group ($p < 0.01$). In the MTP joint, both of the active and passive ROMs-Rest of the DFU group were significantly smaller than these of the DM group ($p < 0.01$) and the DPN group ($p < 0.05$).

3. Gait analysis

3-1. Joint angle in each frame during walk

As results of comparing joint angles in each walking phase among 3 groups (Figure 3), angles of hip joint in the DM group are smaller than these in the DPN and DFU groups during almost all walking phases, and the hip joint angle in the DPN group was significantly larger than in DM group at the Initial Swing phase. Concerning the knee joint, the decrease of the joint angle of the DFU group was characteristic at the swing phase. Limitations of the ankle joint angle were observed in the DFU group in the stance and swing phase although no significant difference was observed. Significant limitations of the MTP joint angle in the DPN and DFU groups at the stance phase. Focusing on the DPN group, the angle of the hip joint was greater than it in the DM group and the joint angle of the knee joint was greater than it in the DFU group in the Initial Swing phase but the angle of the MTP joint was significantly lower than in the DM group in the Pre swing phase.

3-2. ROM during walk (ROM-Walk)

Regarding angles of ROM-walk of hip joint, no significant difference was observed among 3 groups (Figure 4). The angles of ROM-walk in the DFU group were significantly smaller than it in the DM group in the knee joint, the ankle joint, and the MTP joint. The angles of ROM-walk in the DPN group were significantly smaller than it in the control group in the MTP joint.

3-3. Distance factor

The step length ratio in the DFU group was significantly smaller than the DM group and DPN groups (Figure 5). The step width ratio in the DFU group was significantly larger than the DM group.

4. The Center of Mass Sway

The average sway distances in the DFU group were larger than the DM and DPN group (Figure 6). Significant difference was observed in the measurements in the condition of foot width 10cm with closed eyes and in the condition of foot width 0cm with open and closed eyes.

Discussion

In the present study, ROMs of the 4 joints in leg were measured in 2 ways which were the ROM-Rest and the ROM-Walk. Decrease in the ROM-Rest and in the ROM-Walk shows joint function limitation at rest and joint ROM limitation during walking, respectively. The angles in the ROM-Rest and the ROM-Walk in both the ankle and MTP joints tended to decrease as diabetic peripheral neuropathy progressed. The limitations of these ROMs were found to be more advanced at the MTP joint than at the ankle joint among the 3 groups. This finding is consistent with distal axonal degeneration in which diabetic peripheral neuropathy emerges from the periphery (13:Cashman CR 2015). On the other hand, significant difference was not detected in the ROM-Rest of the hip and knee joint. However, we found significant difference in the ROM-Walk of the knee joint in the DFU group. These results revealed that the DFU patients don’t have functional limitations of the knee joint at the resting position but have the limitations of the ROM in the knee joint in their walking behavior. Interestingly, significant limitation of ankle joint motion was not found in each walking phase although the significant difference was observed in the ROM-Rest and ROM-Walk between the DM group and the DFU group. Previous studies in clinical population have yielded conflicting results, particularly at ankle joint motion (14:Rao S, Saltzman, 15:Yavuzer G, 16:Sacco IC). It is thought that the joint function limitation and joint ROM limitation in the ankle joint of DFU patients was able to be measured in the present study.

To observe the results of the joint angles in each phase, characteristics of gait in each group can be revealed. The joint angles at the ankle and MTP joint in the DM group tended to be more than these in DPN and DFU groups, however, concerning the hip joint, flexion in the swing phase of the DM group were less than that of the DPN group, especially at the initial swing phase. The effect of diabetic neuropathy on the motion at the hip has been unclear. Two studies found a decrease in the range of hip flexion in DPN patients when compared with non-diabetic participants (5:Raspovic, 15:Yavuzer G). However, Gomes et al. (17:Gomes AA) found an increase in flexion at the hip in patients with DPN, which they believed was due to a compensatory effect for the loss of motion at distal joints. Our results support the complementary motion of the hip joint observed in the DPN group.

Our analysis for distance factors revealed decreased step length and increased step width in the DFU group. The significant difference in the distance factors and in the joint ROM limitation observed between the DM and DFU groups in the present study are suggesting that these changes are manifested after the appearance of foot ulcers. However, similar changes have been reported even in DM patients without neuropathy compared to participants without DM (15:Yavuzer G 2006). Few researches have simultaneously measured these distant factors among patient groups with/without DM and with/without neuropathy, and further research is needed to determine how advanced diabetes progresses to abnormalities related to the step length and width.

Results of our 4 measurements in the sway distance showed significant increase in the DFU group. It is pointed out that damage to vestibular, autonomic, and somatic nerves with DM peripheral neuropathy affects to gait stability (18:Resnick HE et al 2000, 19:Petrofsky J 2005). The vestibular neuropathy often precedes the loss of sensation in the feet (20:Di Nardo W et al 1999). The group II afferent fibers, which are sensory nerves from muscle spindles, play an important role in feedback control under static and dynamic conditions including the stance phase of walking. It is assumed that the conduction velocity of II fibers is reduced in patients with DM peripheral neuropathy (21:Nardone A 2006, 22:Nardone A 2014). The increase in the sway distance found in the present study is thought to be related with these kinds of peripheral neuropathy and to be associated with the increase of step-width ratio. We believe that dynamic control of balance during gait is impaired with the progression of DM peripheral neuropathy and that compensating for the instability by increasing of the step width prevents falls during gait (23:Allet L et al 2008). The primary measurements on previous articles were gait speed and step length but the importance of step width has often been underestimated

(24:Lamola et al 2015). Furthermore, mass sway has been studied in relation to fall risk, but its association with gait style has been less frequently reported. We think that the body mass sway potentially affects their gait, especially step width. After joining the results of the distant factors, joint ROM limitations, and joint function limitation, it can be assumed that as diabetic peripheral neuropathy progresses, the gait becomes "shuffle walking" with small step length, wide step width, and little movement below the knee joint. As results of the present study, it is assumed in DFU group that there is a mixture of functional limitation of the joints themselves and changes in gait due to decreased ability to maintain center of gravity. In this study, we measured center of mass sway using the Wii Fit, which has been reported to be as accurate as a force platform (25:Clark et al 2010). Because it is portable, widely available, and less expensive than a force platform, we believe it is a suitable tool for standing balance assessment in general clinical practice.

Although the shuffle walking and the enlarged step width leads to a stable gait to avoid falling during walking, the increase of pressure and shear force in plantar possibly induce callositas formation and lead to foot ulceration. A limitation of this study is that no measurement of plantar pressure, which is affected by changes in gait, was performed. Future study should be performed in relation between gait changes and planter pressure. In the present study, joint restrictions, distance factor and mass sway abnormalities were not significantly different in the DPN group compared to the DM group, but were significantly more pronounced in the DFU group. It is thought to be important to detect DPN in early stage of DM condition and to delay or stop the transition to DFU by controlling blood glucose and using walking aids such as insole or orthopedic shoes.

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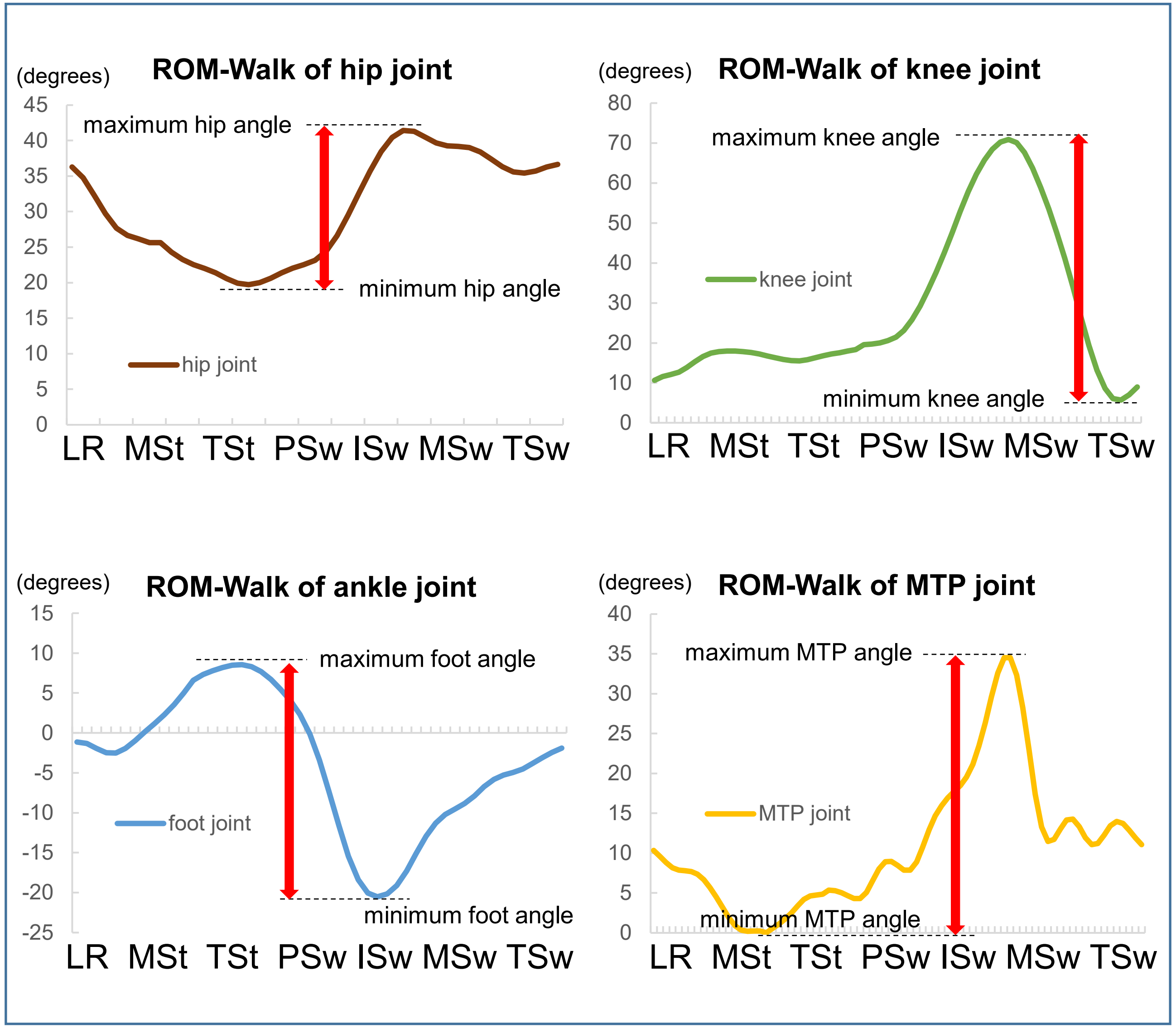
(degrees)
ROM-Walk of hip joint
45
40
35
30
25
20
15
10
5
0
maximum hip angle
minimum hip angle
hip joint
LR MSt TSt PSw ISw MSw TSw
(degrees)
ROM-Walk of knee joint
80
70
60
50
40
30
20
10
0
maximum knee angle
knee joint
minimum knee angle
LR MSt TSt PSw ISw MSw TSw
(degrees)
ROM-Walk of ankle joint
15
10
5
0
-5
-10
-15
-20
-25
maximum foot angle
foot joint
minimum foot angle
LR MSt TSt PSw ISw MSw TSw
(degrees)
ROM-Walk of MTP joint
40
35
30
25
20
15
10
5
0
maximum MTP angle
MTP joint
minimum MTP angle
LR MSt TSt PSw ISw MSw TSw

Fig. 1

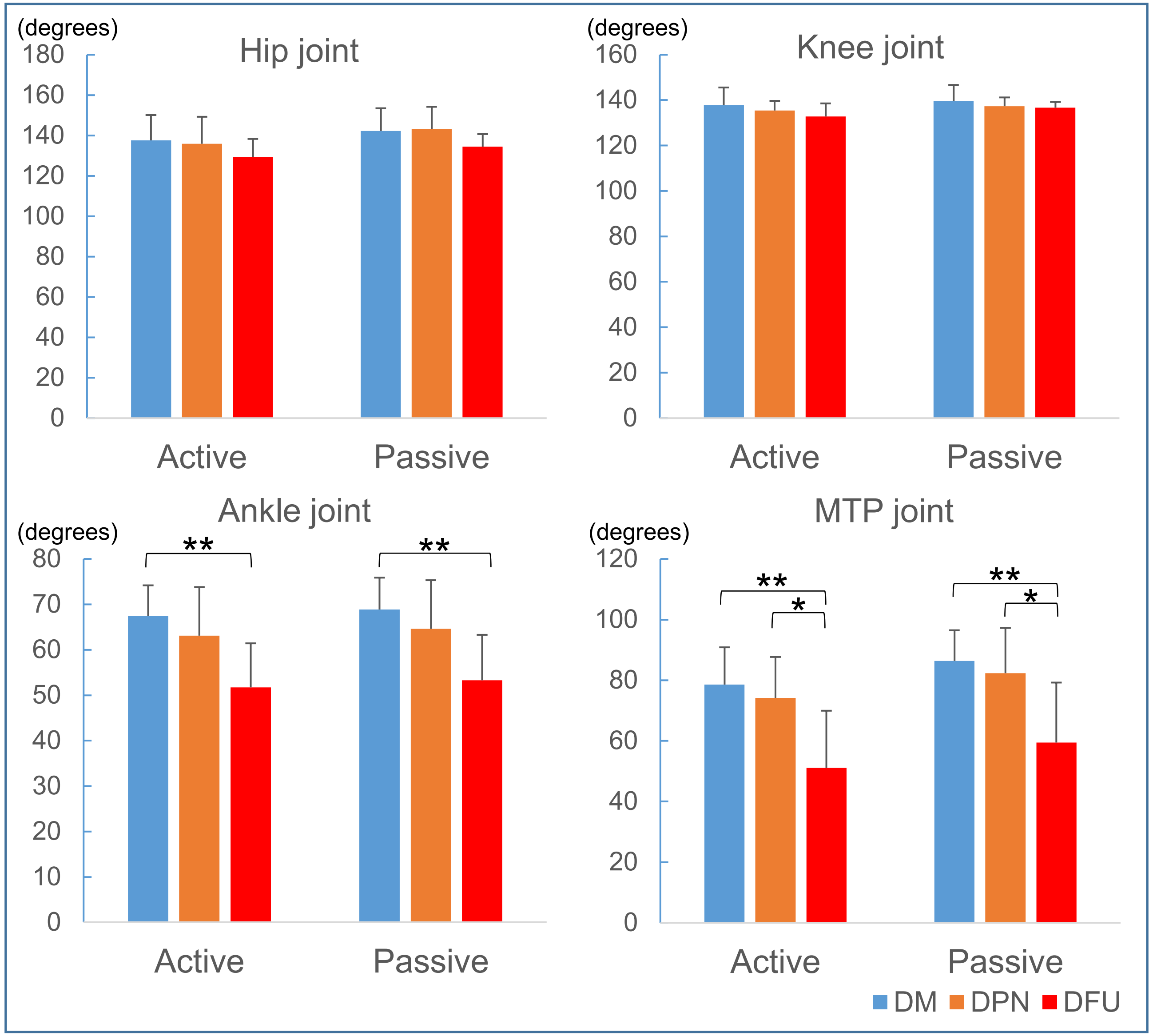
Hip joint
(degrees)
180
160
140
120
100
80
60
40
20
0
Active
Passive
Knee joint
(degrees)
160
140
120
100
80
60
40
20
0
Active
Passive
Ankle joint
(degrees)
80
70
60
50
40
30
20
10
0
**
**
Active
Passive
MTP joint
(degrees)
120
100
80
60
40
20
0
**
*
**
*
Active
Passive
DM
DPN
DFU

Fig. 2

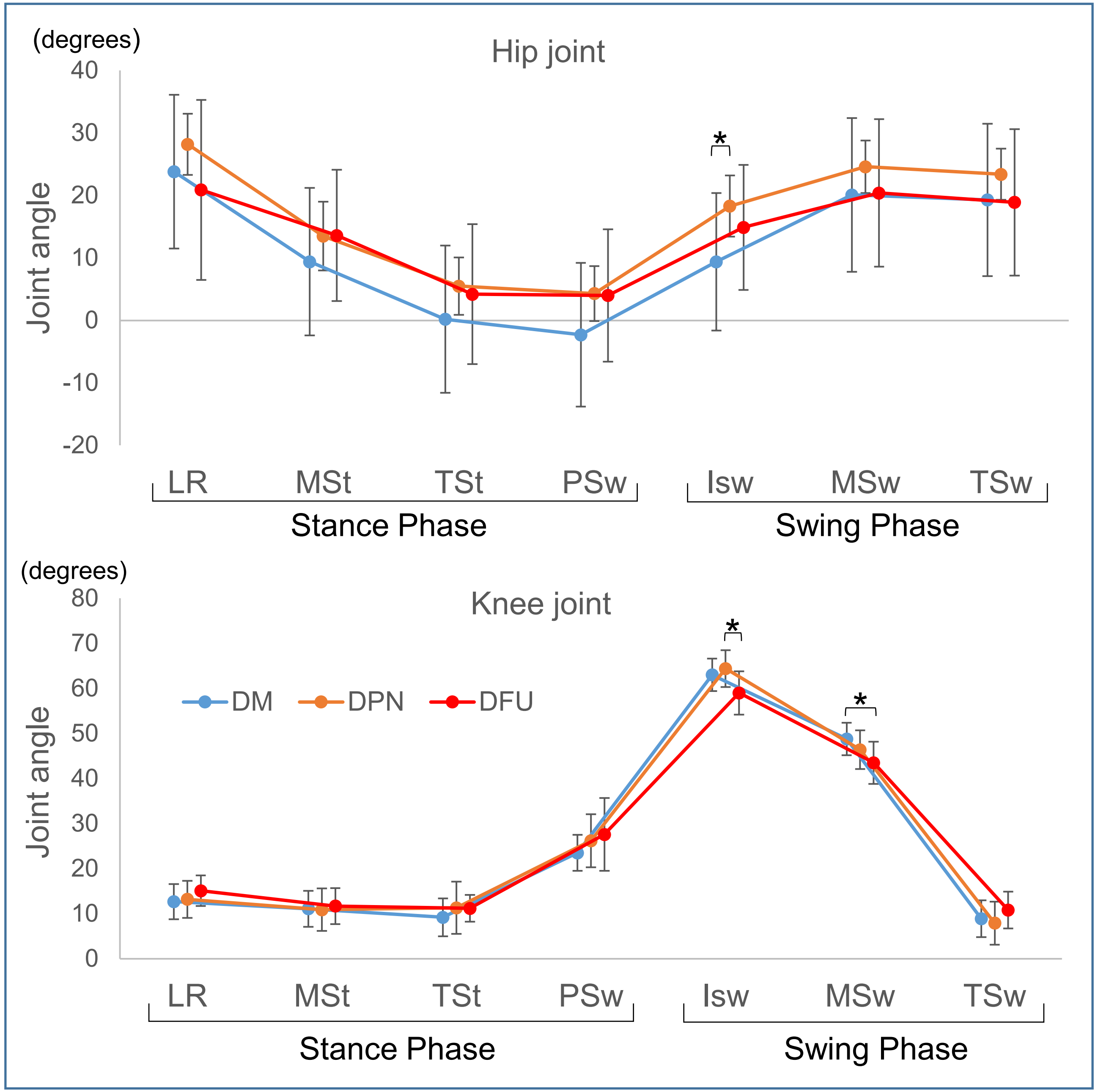
(degrees)
Hip joint
40
30
20
10
0
-10
-20
Joint angle
*
LR
MSt
TSt
PSw
Isw
MSw
TSw
Stance Phase
Swing Phase
(degrees)
Knee joint
80
70
60
50
40
30
20
10
0
Joint angle
DM
DPN
DFU
*
*
LR
MSt
TSt
PSw
Isw
MSw
TSw
Stance Phase
Swing Phase

Fig. 3A

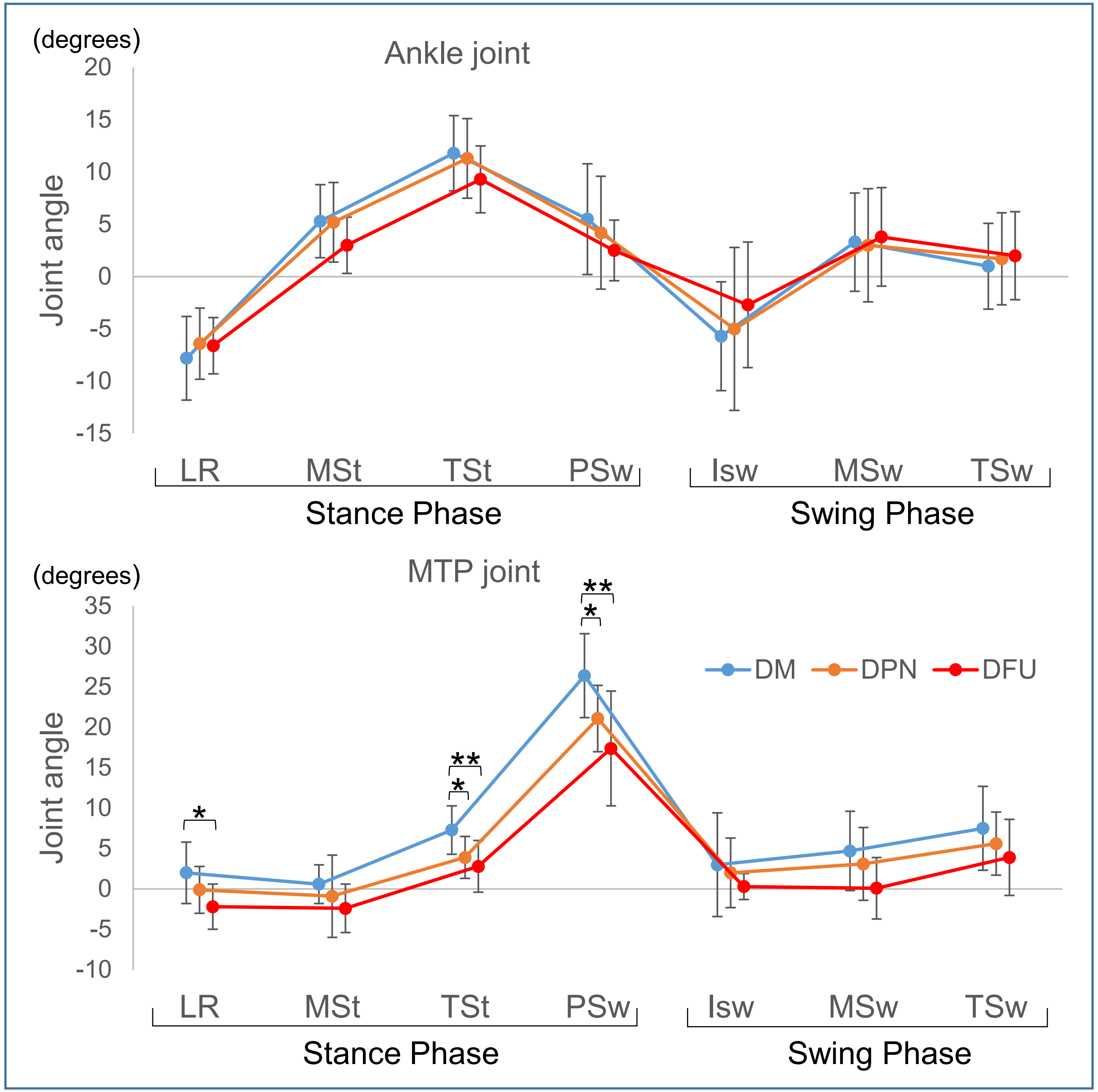
(degrees)
Ankle joint
Joint angle
20
15
10
5
0
-5
-10
-15
LR
MSt
TSt
PSw
Isw
MSw
TSw
Stance Phase
Swing Phase
(degrees)
MTP joint
Joint angle
35
30
25
20
15
10
5
0
-5
-10
*
**
*
**
*
DM
DPN
DFU
LR
MSt
TSt
PSw
Isw
MSw
TSw
Stance Phase
Swing Phase

Fig. 3B

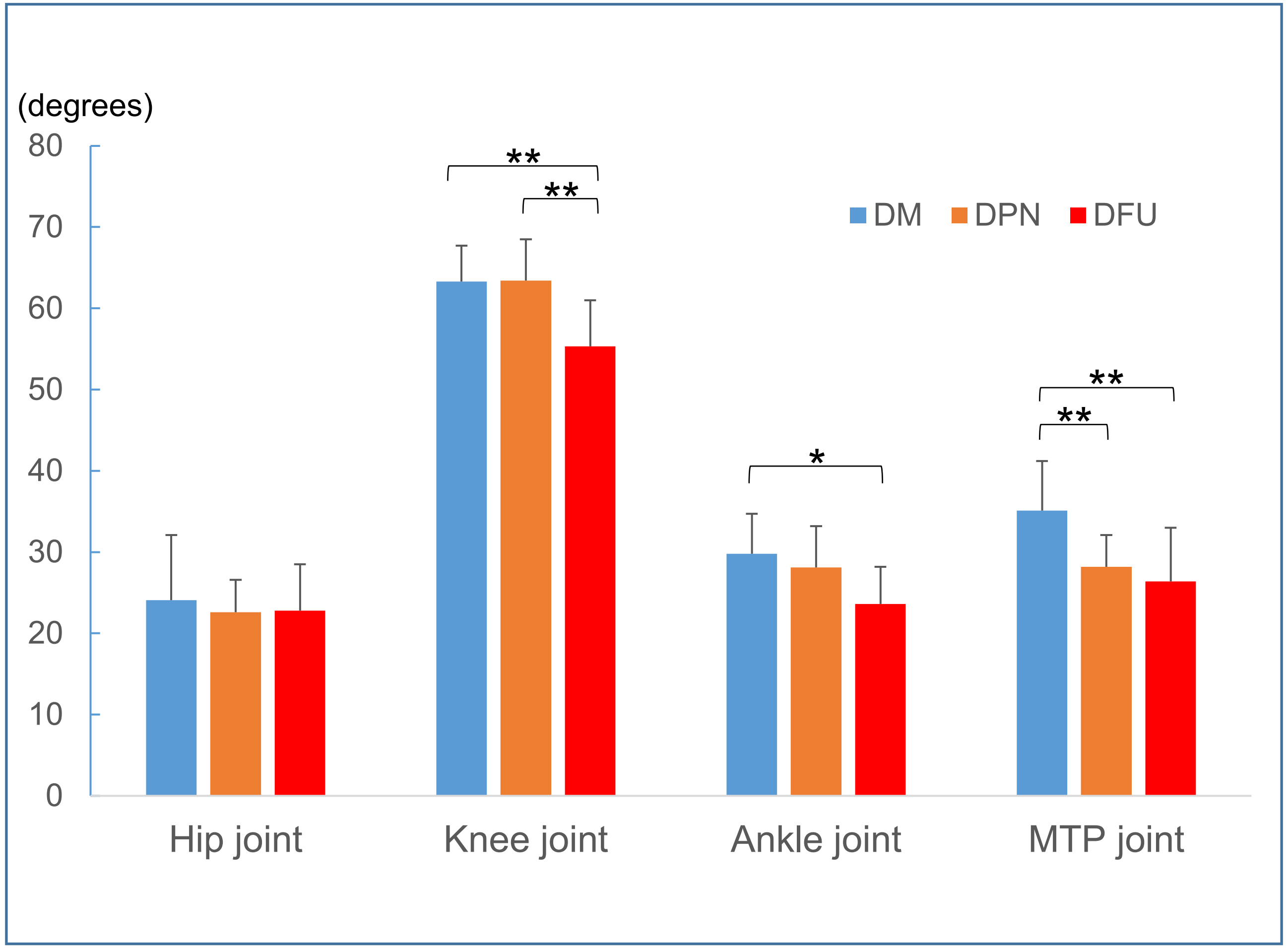
(degrees)
80
70
60
50
40
30
20
10
0
DM
DPN
DFU
**
**
*
**
**
Hip joint
Knee joint
Ankle joint
MTP joint

Fig. 4

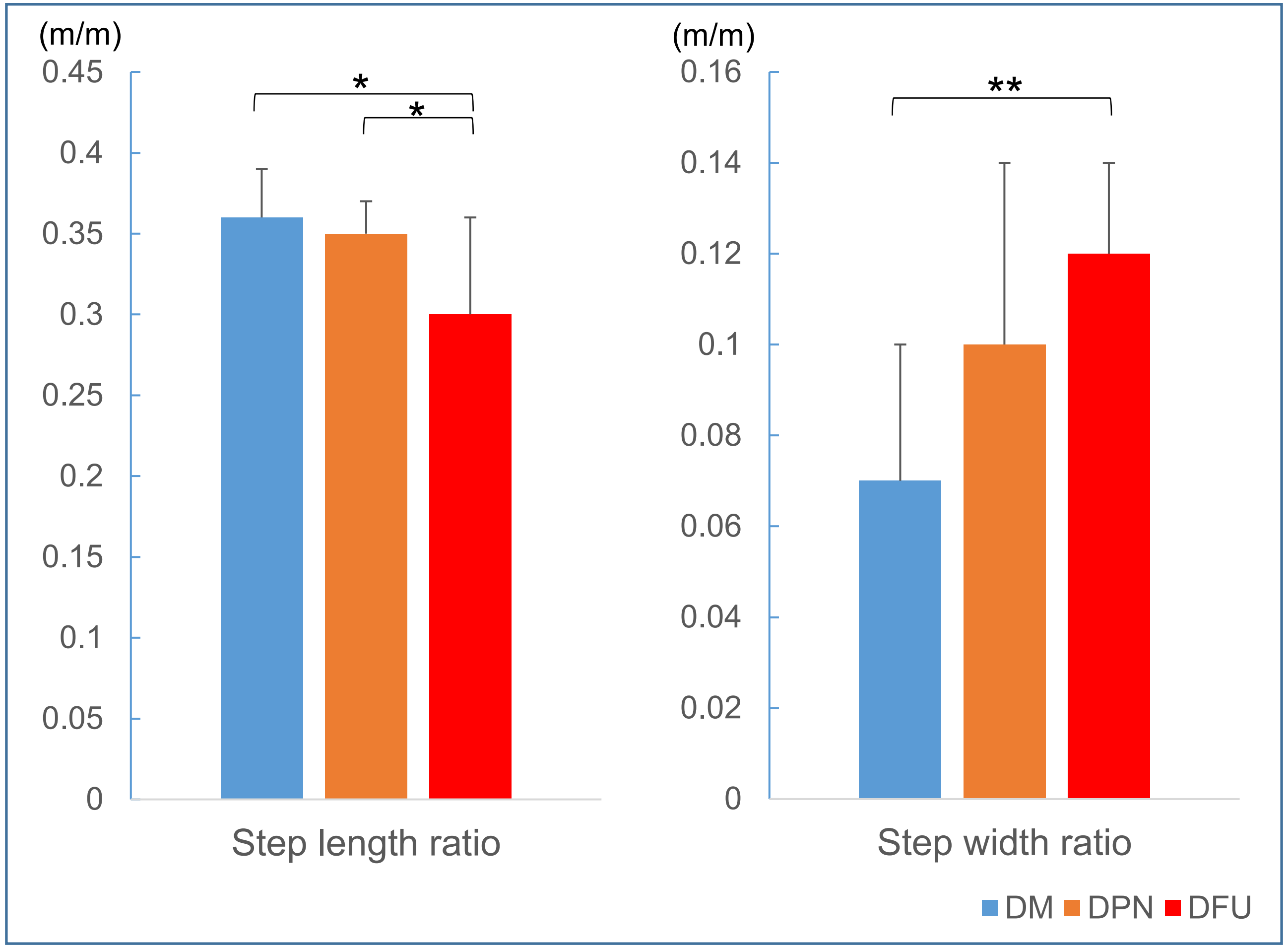
(m/m)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
*
*
Step length ratio
(m/m)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
**
Step width ratio
DM
DPN
DFU

Fig. 5

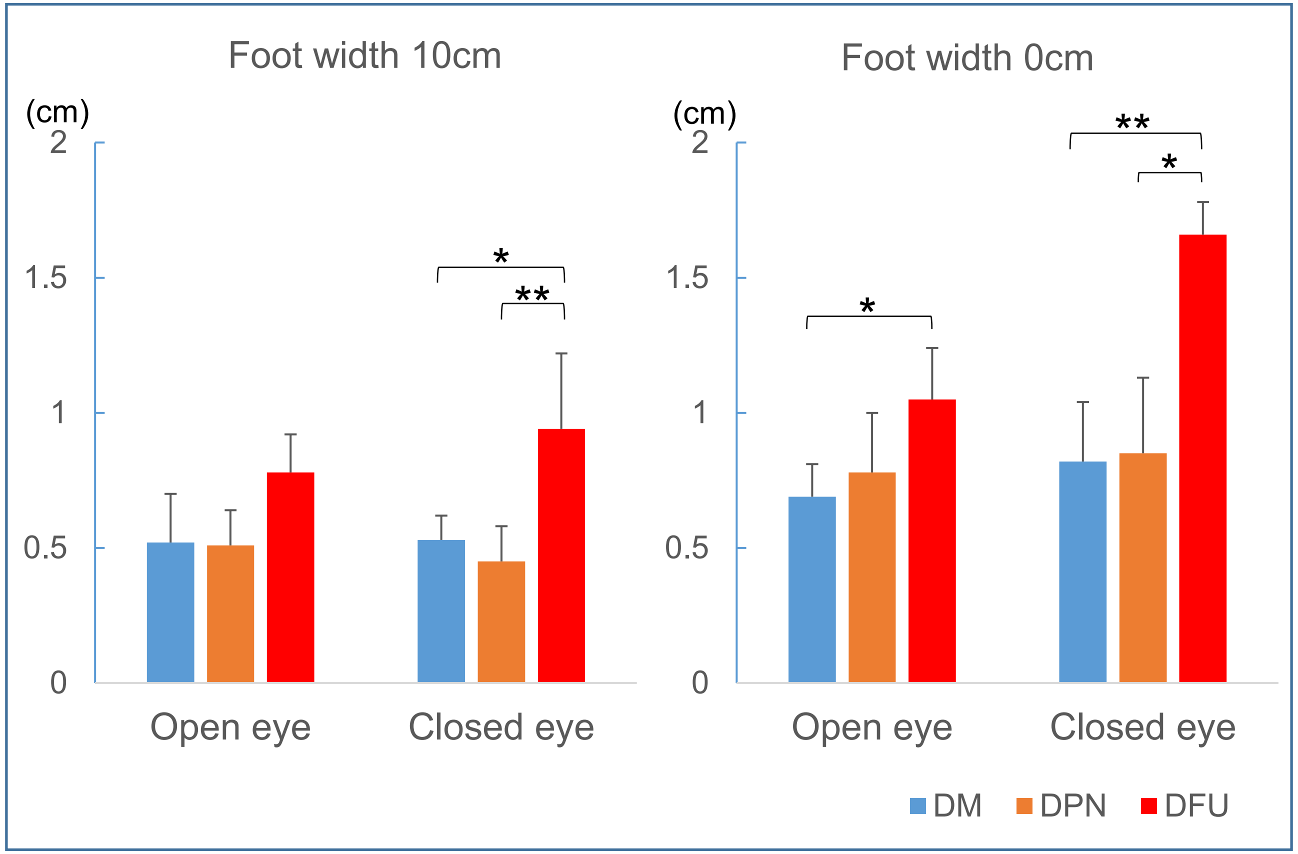
Foot width 10cm
(cm)
2
1.5
1
0.5
0
*
**
Open eye
Closed eye
Foot width 0cm
(cm)
2
1.5
1
0.5
0
*
**
*
Open eye
Closed eye
DM
DPN
DFU

Fig. 6

Table 1. List of measurements in the study

Measurements	**Definition/ Method**
1. Range of Motion (ROM)	
1-1. ROM at Resting Position (ROM-Rest)	Active and passive ROM measured at resting position
1-2. Joint angle in each frame during walk	Analyzing joint angle through 3 reflective markers in each walking phase during walking
1-3. ROM during walk (ROM-Walk)	Difference between the maximum and minimum angle on each joint in a walking cycle
2. Distant factors	
2-1. Step length ratio	Distance between bilateral heel markers measured from the side in a walking cycle divided by height.
2-2. Step width ratio	Distance between bilateral heel markers measured from the front in a walking cycle divided by height.
3. Center of mass sway	
3-1. Average sway distance	Average distance between the center of the device and the center of mass of the subject

Table 2. Clinical characteristics of the subject groups

Group	DM	DPN	DFU	p-value
n (man/woman)	20 (8/12)	15 (10/5)	11 (7/0)	
Age (years)	59.2±13.9	57.8±17.3	60.3±13.8	0.943
Body weight (kg)	63.2±16.4	65.1±10.7	77.5±18.2	0.058
Height (㎝)	158.3±8.9	163.1±8.6	172.8±9.2	0.007
BMI (kg/m^2)	25.1±5.0	24.4±2.7	25.7±4.2	0.690

Values are shown as mean±SD.

DM: diabetes mellitus without diabetic peripheral neuropathy, DPN: diabetic peripheral neuropathy without foot ulcer history,

DFU: diabetic peripheral neuropathy with foot ulcer history, BMI: body mass index