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Comparison of foot segmental mobility and coupling during gait between patients with diabetes mellitus with and without neuropathy and adults without diabetes ☆

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ABSTRACT

Background: Reduction in foot mobility has been identified as a key factor of altered foot biomechanics in individuals with diabetes mellitus. This study aimed at comparing in vivo segmental foot kinematics and coupling in patients with diabetes with and without neuropathy to control adults.
Methods: Foot mobility of 13 diabetic patients with neuropathy, 13 diabetic patients without neuropathy and 13 non-diabetic persons was measured using an integrated measurement set-up including a plantar pressure platform and 3D motion analysis system. In this age-, sex- and walking speed matched comparative study; differences in range of motion quantified with the Rizzoli multisegment foot model throughout different phases of the gait cycle were analysed using one-way repeated measures analysis of variance (ANOVA). Coupling was assessed with cross-correlation techniques.
Findings: Both cohorts with diabetes showed significantly lower motion values as compared to the control group. Transverse and sagittal plane motion was predominantly affected with often lower range of motion values found in the group with neuropathy compared to the diabetes group without neuropathy. Most significant changes were observed during propulsion (both diabetic groups) and swing phase (predominantly diabetic neuropathic group). A trend of lower cross-correlations between segments was observed in the cohorts with diabetes.
Interpretation: Our findings suggest an alteration in segmental kinematics and coupling during walking in diabetic patients with and without neuropathy. Future studies should integrate other biomechanical measurements as it is believed to provide additional insight into neural and mechanical deficits associated to the foot in diabetes.
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1. Introduction

It has been well documented that foot biomechanics can be dramatically altered in persons with diabetes mellitus (DM) (Cavanagh et al., 2005). Joint stiffness and reduction in intrinsic foot mobility have been identified as key factors underlying altered foot biomechanics in individuals with DM (Rao et al., 2010). Factors contributing to this general stiffness and hypomobility are multiple and are often categorized under the umbrella of neural and mechanical deficits (Kwon et al., 2003; Turner et al., 2007; Williams et al., 2007). Researchers typically tend to explore these deficits separately; however, evidence suggests a complex interaction between both (Cronin et al., 2010).

Nonenzymatic soft-tissue glycosylation is believed to play a crucial role in the development of both deficits, especially as it causes limited joint mobility (Campbell et al., 1985; Zimny et al., 2004). Range of motion (RoM) tested passively by a simple goniometer is the most

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commonly used technique to diagnose limited joint mobility, with studies showing a higher degree of limited joint mobility at the subtalar-, tibiotalar- and first metatarsophalangeal joint in diabetic patients with neuropathy and a history of ulceration compared to diabetic patients without neuropathy and non-diabetics (Birke et al., 1995; Viswanathan et al., 2003). However, the clinical relevance of passive RoM testing has been questioned as a considerable discordance between passive RoM and conventional 3D gait analysis has been observed in adults with and without DM and with or without peripheral neuropathy or with an active ulcer (Rao et al., 2006; Turner et al., 2007; Youberg et al., 2005).

While studies using dynamic measurements are thought to be important, results were limited as dynamic foot mobility was only modelled at the hallux and the tibiotalar joint. More recently, 3D multisegment foot models (3DMFMs) emerged allowing the quantification of the mobility of different foot segments during clinical gait analysis (Baker and Robb, 2006; Deschamps et al., 2011). The clinical usefulness of this method with respect to pathomechanical modelling has been underpinned with methodological as well as clinical studies in different patient populations (Deschamps et al., 2012a, 2012b; Ness et al., 2008). So far, clinical usefulness of this segmental modelling in patients with DM has been explored by two different research groups (Rao et al., 2007; Sawacha et al., 2009). Both groups observed significant reduction in segmental foot mobility, especially in the rearfoot and first metatarsal, in patients with DM and peripheral neuropathy. Rao et al. (2007) used an age-, sex and speed matched design and focused on the stance phase of gait in their adults with DM and peripheral neuropathy. The study of Sawacha et al. (2009) is somehow complementary to the latter study, as they have focused not only on stance but also on swing phase of gait. Even though the aforementioned studies provided new insights on impairments in segmental foot behaviour, a number of questions remain unanswered.

First, as both studies omitted to include a DM population without peripheral neuropathy, it is impossible to relate the observed kinematic findings to either peripheral neuropathy, diabetes or both. The effect of peripheral neuropathy on gait dynamics is of clinical interest, as it has been assumed to contribute to general stiffness of the lower limb due to altered afferent feedback (Kwon et al., 2003; Nielsen and Sinkjaer, 2002). Second, kinematic synchrony (coupling) between segments of the foot and tibia has not been addressed by these authors. However, it has been well-documented that actions of the tibia and foot are coupled and that perturbations such as deformity, altered geometry of external loads, reduced flexibility and muscle dysfunction/weakness may induce pathology (Ferber and Pohl, 2011; Hamill et al., 1999). Thus, analysing this biomechanical coupling is relevant as all the aforementioned perturbations have, to some extent, been observed in multiple diabetic cohorts (Wrobel and Najafi, 2010).

Finally, one should be aware of the fact that 3DMFM is not an endpoint in foot function analysis. On the contrary, it is a valuable element in the development of integrated approaches (Sawacha et al., 2012). A typical example is the integration of plantar pressure technology and 3D foot kinematic analysis together with clinically oriented data management, modelling and interpretation. In fact, it is believed that the combination of these elements makes it possible to reach a higher dimension for the interpretation of a clinical complex phenomenon (Guiotto et al., 2013).

Thus, while neural and mechanical deficits have been identified as important factors to foot and lower limb function, the role of segmental mobility and coupling remains poorly understood.

The present study tested two specific null hypotheses amongst two groups of patients with diabetes (group 1 = patients with DM and neuropathy (PwDM_NP), group 2 = patients with DM without neuropathy (PwDM_noNP)) and a non-diabetic control group (Ctrl group): i) dynamic multi-segment foot motion is not affected in PwDM_NP and PwDM_noNP, and ii) kinematic coupling between segments of the foot and tibia is not altered in PwDM_NP and PwDM_noNP.

2. Methods

2.1. Subjects

Individuals were selected from an on-going multi-centre study including three Belgian Diabetic Foot Clinics following Local Research Ethical approval. This study started in 2010 and recruited in total 97 patients with DM and 33 healthy control subjects over a one year period (total group N = 130). Inclusion criteria for the subjects with DM were: type 1 or type 2 diabetes, walking ability, no active foot ulcer or amputation, no history of orthopaedic lower limb surgery and no Charcot neuroarthropathy. Following recruitment in each clinic, a study-specific medical record and standard clinical examination was completed. Inclusion criteria for the Ctrl group were: age between 45 and 70 years, BMI between 20 kg/m^2 and 40 kg/m^2, no history of orthopaedic lower limb surgery, and absence of any known neurological or systemic disease.

2.2. Data acquisition

Gait analysis of all recruited individuals was performed in the Laboratory for Movement Analysis University Hospitals of Leuven using the following measurement devices: a 3D motion analysis system, a plantar pressure platform, and a force platform. A passive motion analysis system (Vicon Motion System Ltd, Oxford Metrics, Oxford, UK) consisting of 10 T-10 cameras was used to track the kinematic data (100 Hz) of all participants while walking over a 10-m walkway at a self-selected comfortable speed. Kinematic data were computed throughout the Vicon Foot model Plug-in (Aurion Srl, Milano, Italy) using Nexus 1.5 software (Vicon Motion System Ltd, Oxford Metrics, Oxford, UK). In the aforementioned walkway, a force plate was placed in the middle (Advanced Mechanical Technology, Newton, MA, US) covered with a pressure plate (RSscan International, Olen, Belgium). The current set-up allowed the detection of specific gait events. Time synchronization between the pressure plate and motion analysis system was achieved by measuring the optimal signal correlation between the force signals of both pressure and force plate (Hagman, 2005). Data from the force plate and pressure plate were sampled at 200 Hz whereas kinematic data was sampled at 100 Hz.

2.3. Measurement protocol and 3DMFM

The first stage of the measurement protocol consisted of placing fourteen six mm retro-reflective markers over the described anatomical landmarks according to the Rizzoli 3D multisegment foot model (Rizzoli_3DMFM) protocol (Leardini et al., 2007). After marker placement, a standing trial in a relaxed position was recorded. Subsequently, the measurements of the dynamic trials started, with individuals walking at a self-selected speed until five 'representative' walking trials were recorded. A trial was considered representative if the participants made clear pedobarograph contact with the foot and closely resembled one another from trial to trial, as defined by visual inspection.

Three-dimensional rotations between shank and calcaneus (Sha-Cal), calcaneus and midfoot (Cal-Mid), midfoot and metatarsus (Mid-Met) as well as calcaneus and metatarsus (Cal-Met) were analysed for each individual from the three study groups (Leardini et al., 2007). The planar angle of the first metatarso-phalangeal joint with respect to the sagittal plane, referred to as F2Ps, was also considered. Inter-segment 3D rotations were calculated following International Society of Biomechanics recommendations (Wu et al., 2002), with dorsiflexion/plantarflexion (sagittal plane = Do/PF) defined as rotation about the medio-lateral axis of the proximal segment, adduction/abduction (transverse plane = Add/Abd) about the vertical axis of the distal segment and

inversion/eversion (frontal plane = Inv/Eve) about an axis orthogonal to the first two axes.

2.4. Matching procedure

In order to investigate in an appropriate way the above mentioned hypotheses, the total group of individuals (n = 130) was first sub-classified based on the presence of DM and the presence of neuropathy. Presence of neuropathy was defined as the inability to perceive the application of a 5.07 monofilament at two or more sites on each foot and the inability to perceive the vibration of the tuning fork (128 Hz) at the apex of both halluces. Subsequently, trios were created by matching subjects on the basis of age- (within a range of five years), sex- (male/female), and self-selected walking speed (within range of 0.2 m s^{-1}). As a consequence of this matching procedure, the following three study groups were created: patients with DM and neuropathy (PwDM_NP, n = 13), patients with DM without neuropathy (PwDM_noNP, n = 13), persons without DM (Ctrl, n = 13).

2.5. Data and statistical analysis

The RoM, defined as the difference between the maximum and minimum value in a kinematic waveform of each inter-segment angle, was calculated for the following phases of gait: full gait cycle (GC), stance, swing, Forefoot Contact Phase (FFCP), Foot Flat Phase (FFP) and Forefoot Push Off Phase (FFPOP). Specific gait events for determining these gait phases were collected from the pressure plate and motion analysis software. The sub phases FFCP, FFP and FFPOP were defined as the duration between respectively the First Foot Contact (FFC) and Forefoot Flat (FFF), Forefoot Flat and Heel Off (HO) and Heel Off and Last Foot Contact (LFC) (De Cock et al., 2005). The events FFC and LFC were used to define the stance phase whereas the events FFC and second-heel strike (collected with motion analysis system) were used to define the complete gait cycle. The adopted subphase classification is an adapted version of the sub-phase classification originally described by De Cock et al. (2005). The calculation of the RoM for the different phases was preceded by time normalization of the data to 100% gait cycle considering multi-event synchronization with all gait events. This post-processing was performed within Matlab with the programme ACEP*Manager* (Advanced Clinical Examination Platform), made by the consortium of authors.

With respect to the statistical analysis, first normal probability plots were graphically represented to check for normality. One-way repeated measures ANOVA (Matlab 2012a, Mathworks) was used to assess differences in RoM during the complete gait cycle between the three groups ($\alpha = 0.05$). In order to have a better exploration of the kinematic behaviour and pattern of the diabetic cohorts, we tested also the hypothesis that RoM measures were the same during the different sub-phases. To control Type I error rate when performing multiple comparisons, an adjusted *P*-value was used ($\alpha/5 = 0.01$). In cases where significant differences were observed, Tukey's honestly test was used to indicate which groups were different.

To examine the degree of kinematic coupling between foot segments and tibia, the cross-correlation coefficient of the angular displacement curves of adjacent segments across the stance phase was calculated (Li and Caldwell, 1999). Based on previous publications (Pohl et al., 2006, 2007), it was decided to analyse the coupling between four inter-segment rotations: 1) Sha-Cal Inv/Eve: Sha-Cal Add/Abd, 2) Sha-Cal Inv/Eve: Cal-Met DF/PF, 3) Sha-Cal Inv/Eve : Cal-Met (Inv/Eve), and 4) Sha-Cal Inv/Eve : Cal-Met Add/Abd. Correlation coefficients (r) greater than 0.7 (or less than −0.7) were considered to represent a strong coupling between two segmental rotations. Coefficients between 0.3 to 0.69 and −0.3 to −0.69 indicated a moderate coupling, and coefficients between −0.3 and 0.3 suggested zero or weak coupling (Pohl et al., 2006).

3. Results

Baseline characteristics of the three groups are presented in Table 1. The three groups had similar mean age and gait speed as a consequence of the matching procedure ($P > 0.05$). A high number of individuals from the PwDM_NP group had a history of foot ulceration (76%); moreover, also a discrete number of individuals from the PwDM_noNP group had a history of ulceration (23%). The mean BMI was significantly higher in the PwDM_NP group ($P = 0.046$), whereas only a trend towards longer diabetes duration was observed in the PwDM_NP compared to the PwDM_noNP group.

The duration of the sub-phases of stance showed significant differences (Additional file 1). Heel Off was found to occur later in the PwDM_NP group compared to the Ctrl group (PwDM_NP = 44.0% gait cycle, Ctrl = 38.4% gait cycle, $P = 0.021$). Hence, FFPOP was found to be shorter in the PwDM_NP Group (PwDM_NP = 20.2% gait cycle, Ctrl = 24.7% gait cycle, $P = 0.029$).

A summary of the one way repeated measures ANOVA statistics conducted on RoM associated to the full gait cycle, stance and swing is provided in Table 2. Similar statistics performed on the RoM observed within each of the three subphases of stance is provided in Table 3 and Fig. 1. From these tables, it can be observed that significant differences were found between the different groups, moreover, these differences were predominantly in the sagittal and transverse plane (Additional file 2).

When considering the stance phase separately (Table 2), both diabetic cohorts showed a significant reduction in RoM between the shank-calcaneus and calcaneus-midfoot (sagittal and transverse plane) compared to the Ctrl group.

For the PwDM_NP, analyses of the subphases of stance illustrated a reduced Sha-Cal Add/Abd during FFCP ($P = 0.0089$) compared to Ctrl group (Table 3 and Fig. 1). The PwDM_NP group showed increased sagittal plane RoM between the calcaneus and metatarsus during this phase compared to Ctrl group. During FFPOP, the PwDM_NP group (13.9°) showed reduced Sha-Cal Do/PF RoM compared to the PwDM_noNP (18.0°) and Ctrl group (20.4°) ($P = 0.0019$). During the same sub-phase, not only the PwDM_NP but also the PwDM_noNP showed reduced sagittal plane RoM between calcaneus and midfoot (Cal-Mid, PwDM_NP = 10.7°, PwDM_noNP = 11.6°, Ctrl = 14.9°, $P = 0.0071$), as well as transverse plane RoM between shank and calcaneus, calcaneus and midfoot as well as midfoot-metatarsus compared to the Ctrl group.

More pronounced differences were observed between both diabetic groups during swing. Here, especially the PwDM_NP showed a reduced

Table 1
Baseline subjects characteristics for the three groups (mean and standard deviation).

	PwDM_NP (n = 13)	PwDM_noNP (n = 13)	Ctrl (n = 13)	*P* value
Age (years)	62.8 (5.6)	63.0 (7.4)	57.7 (5.1)	n.s.
Gender M/F ratio	12/1	12/1	12/1	–
Diabetes type 1/2	2/11	2/11	–	–
Height (cm)	178.6 (7.5)	174.0 (6.8)	176.7 (7.1)	n.s.
Weight (kg)	95.4 (16.4)	83.7 (16.4)	84.5 (17.3)	n.s.
BMI (kg/m^2)	29.8 (4.3)	27.5 (4.4)	26.9 (4.2)	0.046
Speed (m s−1)	1.10 (0.16)	1.09 (0.16)	1.20 (0.13)	n.s.
Stance time (% gait cycle)	61.4 (1.6)	60.5 (2.2)	60.2 (2.0)	n.s.
Cadence (steps/min)	104.9 (8.2)	104.2 (8.1)	108.3 (5.5)	n.s.
Diabetes duration (years)	19.3 (9.7)	12.2 (9.2)	—	n.s.
HbA1c (%)	7.7 (0.7)	6.9 (1.0)	—	—
History of ulceration (n)	10	3	—	—
<2 pulses (PVD)	2	3	0	—
Custom made foot orthoses (n)	8	2	0	—

PwDM_NP: Diabetics with neuropathy; PwDM_noNP: Diabetics without neuropathy; Ctrl: Control group, PVD = peripheral vascular disease (assessed by palpation of the dorsalis pedis and tibial pulses on both feet).

Table 2
Summary of mean range of motion and standard deviation (in degrees) during full gait cycle, stance and swing phase for all three groups.

		Full gait cycle				Stance				Swing			
		PwDM_NP (1)	PwDM_ noNP (2)	Ctrl (3)	*P* value	PwDM_NP (1)	PwDM_ noNP (2)	Ctrl (3)	*P* value	PwDM_NP (1)	PwDM_ noNP (2)	Ctrl (3)	*P* value
Sha-Cal	Do/PF	16.5 (2.7)[a]2,3	19.7 (3.0)[a]1	20.6 (4.2)[a]1	0.0099	16.0 (2.6)[b]3	19.3 (3.2)	20.4 (4.1)[b]1	0.019	10.5 (3.5)[a]2,3	15.8 (4.0)[a]1	17.3 (4.5)[a]1	0.0018
	Inv/Eve	7.3 (1.6)	7.7 (1.3)	8.2 (1.6)	n.s.	6.1 (1.4)	7.1 (2.0)	7.4 (1.4)	n.s.	3.6 (1.2)	4.1 (1.0)	4.3 (1.0)	n.s.
	Add/Abd	7.3 (1.7)[a]2,3	9.7 (2.0)[a]1	11.6 (2.6)[a]1	0.0008	6.2 (2.4)[a]3	8.9 (2.2)	10.5 (2.4)[a]1	0.0016	5.6 (1.1)[a]3	6.6 (1.8)[a]3	8.7 (2.3)[a]1,2	0.0015
Cal-Mid	Do/PF	11.4 (3.1)[b]3	11.9 (2.2)	14.9 (3.6)[b]1	0.019	11.1 (2.9)[a]3	11.7 (2.3)[a]3	14.9 (3.6)[a]1,2	0.0093	4.1 (1.4)[a]3	5.8 (2.2)	8.2 (3.6)[a]1	0.0051
	Inv/Eve	7.2 (1.4)	6.5 (1.8)	7.9 (1.3)	n.s.	6.5 (0.9)	6.0 (1.5)	6.1 (1.1)	n.s.	3.1 (0.6)[a]3	3.9 (1.3)[a]3	5.6 (1.1)[a]1,2	0.0001
	Add/Abd	7.6 (2.3)[a]3	7.4 (1.9)[a]3	10.3 (2.2)[a]1,2	0.0028	6.9 (2.5)[a]3	7.1 (2.1)[a]3	10.3 (2.5)[a]1,2	0.0022	3.7 (1.6)[a]3	4.7 (1.2)	6.1 (2.1)[a]1	0.0044
Mid-Met	Do/PF	6.8 (1.8)	5.7 (1.1)	6.6 (1.7)	n.s.	6.8 (1.8)	5.7 (1.1)	6.6 (1.7)	n.s.	3.1 (0.5)[b]3	3.9 (1.2)	4.6 (1.2)[b]1	n.s.
	Inv/Eve	4.9 (0.9)	4.1 (0.8)	4.2 (1.0)	n.s.	4.9 (0.9)	4.1 (0.8)	4.2 (1.0)	n.s.	1.9 (0.4)	2.3 (0.4)	2.3 (0.5)	n.s.
	Add/Abd	6.3 (2.3)	6.1 (1.0)	8.0 (1.8)	n.s.	6.3 (2.3)	6.1 (1.0)	8.0 (1.8)	n.s	2.8 (0.6)	2.9 (0.8)	3.2 (1.2)	n.s.
Cal-Met	Do/PF	13.9 (3.2)	12.3 (1.9)	14.5 (4.8)	n.s.	13.9 (3.2)	12.3 (1.9)	14.5 (4.8)	n.s.	4.3 (0.8)[a]3	6.4 (1.9)	9.2 (4.2)[a]1	0.0023
	Inv/Eve	8.2 (2.8)[b]3	8.8 (2.1)	11.0 (2.8)[b]1	n.s.	8.2 (2.8)	8.8 (2.1)	11.0 (2.8)	n.s	4.0 (1.6)[a]2,3	6.0 (1.4)[a]1	6.8 (2.5)[a]1	0.005
	Add/Abd	9.8 (2.6)[a]2	7.9 (1.5)[a]1,3	10.8 (1.7)[a]2	0.0051	9.8 (2.6)[a]2	7.9 (1.5)[a]1,3	10.8 (1.7)[a]2	0.0044	4.2 (0.7)[a]3	5.2 (1.7)[a]3	7.1 (1.3)[a]1,2	0.0001
F2Ps	Do/PF	37.4 (8.6)	37.7 (4.4)	39.1 (6.2)	n.s	35.2 (9.6)	37.4 (4.6)	39.1 (6.3)	n.s.	17.0 (5.7)	16.7 (3.9)	17.1 (3.5)	n.s.

PwDM_NP: Diabetic Group with neuropathy, PwDM_noNP: Diabetic Group without neuropathy, Ctrl: Control Group.
Sha-Cal: Shank-Calcaneus, Cal-Mid: Calcaneus-Midfoot, Mid-Met: Midfoot-Metatarsus, Cal-Met: Calcaneus-Metatarsus, F2Ps = hallux or first metatarsaophalangeal joint Do/PF: Dorsiflexion/Plantarflexion, Inv/Eve: Inversion/Eversion, Add/Abd: Adduction/Abduction.
[a] Indicates significant difference between groups (one-way repeated measures ANOVA, $P < 0.01$), n.s. = not significant.
[b] Indicates significant difference between groups (groups are coded with a number) (one-way repeated measures ANOVA, $P < 0.05$).

RoM. These alterations predominantly occurred between the Sha-Cal, Cal-Mid and Cal-Met (Table 2).

Coupling between Sha-Cal Inv/Eve and Sha-Cal Add/Abd was high in the Ctrl group and PwDM_noNP group whereas the coupling between Sha-Cal Inv/Eve and Cal-Met Do/PF was only high in the Ctrl group (Table 4). The PwDM_NP group was characterized by a poor correlation with respect to both aforementioned inter-segment coupling.

4. Discussion

In this study, segmental foot mobility was compared between patients with DM with and without neuropathy and adults without diabetes using the Rizzoli_3DMFM protocol (Leardini et al., 2007). Both diabetic cohorts showed a decreased RoM during the propulsive phase (FFPOP) between the Sha-Cal, Cal-Mid and Cal-Met compared to the Ctrl group. More differences were observed between both diabetic groups through swing, where especially the PwDM_NP demonstrated less range of motion. The synchronous motion between specific segments was also found to be altered.

A noteworthy finding provided by the integrated measurement set-up is the altered temporal loading of foot segments during stance in the PwDM_NP group. A delayed heel off was detected in this group ($P = 0.021$). A more conservative walking strategy can be considered as a plausible explanation, as this is characterized by a less prominent propulsive phase (Giacomozzi et al., 2002). This assumption can be further underpinned by the fact that the FFPOP was significantly shorter in the PwDM_NP group (Additional file 1). These sub-phases of stance were also incorporated in the analysis of the kinematic data as basis for searching significant differences between the three cohorts. This is the most commonly adopted approach in kinematic research amongst other techniques which also aim at detecting significant differences between waveforms of different clinical populations (De Ridder et al., 2013; Deluzio and Astephen, 2007).

The PwDM_NP group was characterized by a considerable difference in multisegment foot kinematics during the swing phase. In this group, a reduced RoM was observed predominantly between the Sha-Cal and Cal-Mid. Compared to the Ctrl group, this may illustrate an altered flexibility and coupling of the musculoskeletal system in an open chain situation; however, this may also be partly related to changes in neuromuscular recruitment of musculature surrounding the ankle (Cronin et al., 2010). Hence, this may implicate that the positioning of the foot prior to initial contact is different in PwDM_NP, with potential repercussions on the foot mechanics during stance. A plausible illustration of the latter is the reduced transverse plane RoM during FFCP in the PwDM_NP group. This lack of transverse plane motion may result in deviated joint coupling between the rearfoot and shank. Evidence for this assumption is provided by the lower cross correlation value between the Sha-Cal Inv/Eve and Sha-Cal Add/Abd (Table 4). In fact, we observed a high coupling between Sha-Cal Inv/Eve and Sha-Cal Add/Abd in the Ctrl group and PwDM_noNP group. These observations differ from the data published by Pohl et al. (2007), who only found a strong correlation during running but not during walking. Another plausible explanation for this lack of shank internal rotation in the PwDM_NP, next to the altered segmental kinematics during swing, may be a co-contraction of tibialis anterior and gastrocnemius during loading response. Such co-contraction has been reported by Kwon et al. (2003) in subjects with neuropathy and is assumed to be a strategy to increase stability and safety. In the perspective of our findings, such co-contraction can be considered to cause rigidity at the foot ankle complex, as premature contraction of the gastrocnemius would preclude adequate deceleration of shank internal rotation during loading response (Andrews et al., 2012). In this perspective, one may consider that the increased sagittal plane RoM between the calcaneus and metatarsus during FFCP and FFP in the PwDM_NP group serves as compensation for facilitating forefoot contact with the ground (Kwon et al., 2003).

Table 3
Summary of mean range of motion and standard deviation (in degrees) during sub phases of stance for the three study groups.

		Forefoot Contact Phase (FFCP)				Foot Flat Phase (FFP)				Forefoot Push Off Phase (FFPOP)			
		PwDM_NP (1)	PwDM_noNP (2)	Ctrl (3)	*P* value	PwDM_NP (1)	PwDM_noNP (2)	Ctrl (3)	*P* value	PwDM_NP (1)	PwDM_noNP (2)	Ctrl (3)	*P* value
Sha-Cal	Do/PF	5.2 (2.3)	4.9 (1.6)	4.4 (0.8)	n.s.	11.0 (2.6)	10.9 (3.0)	10.7 (1.4)	n.s.	13.9 (2.7)[a]2,3	18.0 (4.0)[a]1	20.4 (4.2)[a]1	0.0019
	Inv/Eve	3.3 (0.7)	3.7 (1.3)	3.4 (1.1)	n.s.	2.0 (0.7)	2.3 (0.9)	2.4 (1.1)	n.s.	4.7 (1.0)	5.4 (1.0)	5.9 (1.3)	n.s.
	Add/Abd	1.9 (0.7)[a]3	2.7 (1.2)	3.9 (1.6)[a]1	0.0089	2.7 (1.1)	3.4 (1.1)	3.1 (0.9)	n.s.	4.4 (1.1)[a]3	5.9 (2.4)[a]3	8.5 (1.9)[a]1,2	0.0001
Cal-Mid	Do/PF	2.4 (1.3)	2.3 (0.8)	1.9 (0.7)	n.s.	5.4 (1.7)	4.3 (1.4)	4.0 (1.2)	n.s.	10.7 (3.2)[a]3	11.6 (2.4)[a]3	14.9 (3.6)[a]1,2	0.0080
	Inv/Eve	3.7 (0.9)	3.7 (1.2)	3.8 (1.2)	n.s.	2.5 (0.7)	2.4 (0.9)	2.3 (0.6)	n.s.	4.4 (1.1)	3.9 (1.2)	4.1 (1.1)	n.s.
	Add/Abd	2.0 (0.7)	1.6 (0.5)	2.1 (1.0)	n.s.	2.9 (0.9)	2.1 (0.5)	2.4 (0.8)	n.s.	6.4 (2.7)[a]3	6.9 (2.2)[a]3	9.9 (2.1)[a]1,2	0.0031
Mid-Met	Do/PF	2.8 (0.7)	2.6 (0.7)	2.0 (0.9)	n.s.	2.3 (1.0)	2.0 (0.5)	1.8 (0.5)	n.s.	5.2 (1.5)	4.4 (1.3)	4.6 (1.8)	n.s.
	Inv/Eve	2.3 (0.8)	1.9 (0.7)	1.8 (0.9)	n.s.	2.0 (0.6)	1.6 (0.3)	1.4 (0.5)	n.s.	3.6 (0.6)	3.4 (0.9)	3.5 (0.8)	n.s.
	Add/Abd	2.4 (1.3)	2.1 (0.9)	2.6 (1.1)	n.s.	1.7 (0.4)	1.7 (1.2)	1.8 (0.5)	n.s.	4.5 (2.1)[a]3	4.7 (0.7)[a]3	6.7 (1.6)[a]1,2	0.0037
Cal-Met	Do/PF	4.9 (1.6)[a]3	4.3 (1.3)	3.2 (0.5)[a]1	0.0076	5.8 (1.9)[a]2,3	3.8 (1.3)[a]1	3.3 (1.4)[a]1	0.0023	13.1 (2.9)	12.1 (1.9)	14.2 (4.7)	n.s.
	Inv/Eve	2.2 (1.1)	1.9 (0.9)	2.3 (0.9)	n.s.	2.8 (1.0)	2.1 (0.6)	2.3 (0.7)	n.s.	6.8 (3.1)[a]3	8.0 (2.4)	10.2 (2.6)[a]1	0.01
	Add/Abd	3.4 (1.2)	2.3 (0.9)	2.4 (0.9)	n.s.	2.5 (0.9)	2.7 (1.2)	2.8 (0.9)	n.s.	7.5 (2.4)	5.6 (0.9)[a]1	8.3 (1.8)[a]2	0.0041
F2Ps	Do/PF	8.7 (3.9)	10.6 (3.9)	9.1 (3.1)	n.s.	13.6 (6.1)	12.1 (2.0)	8.9 (4.2)	n.s.	31.2 (8.1)	33.9 (4.8)	36.7 (5.7)	n.s.

PwDM_NP: Diabetic Group with neuropathy, PwDM_noNP: Diabetic Group without neuropathy, Ctrl: Control Group. Sha-Cal: Shank-calcaneus, Cal-Mid: Calcaneus-Midfoot, Mid-Met: Midfoot-Metatarsus, Cal-Met: Calcaneus-Metatarsus, F2Ps: hallux or first metatarsaophalangeal joint, Do/PF: Dorsiflexion/Plantarflexion, Inv/Eve: Inversion/Eversion, Add/Abd: Adduction/Abduction.
[a] Indicates significant difference between groups (groups are coded with a number) (one-way repeated measures ANOVA, $P < 0.01$), n.s. = not significant.

An adequate second rocker (FFP) was observed in both diabetic groups, indicating that the forward progression of the tibia is not precluded which is in agreement with recent observations (Rao et al., 2007; Turner et al., 2007). Contrarily, a general trend towards reduced RoM during FFPOP in both groups with diabetes was observed (Tables 2–3 and Fig. 1). The observed reduction of plantarflexion between the Sha-Cal during FFPOP in the PwDM_NP reflects a deviant third rocker and is probably related to the above mentioned 'cautious walking strategy' (Giacomozzi et al., 2002). Kerrigan et al. (1998) observed a similar reduction in ankle plantarflexion in elderly subjects and inferred it as an adaptive strategy to maintain greater foot-to-floor contact during terminal stance. Reduced plantar flexor muscle strength may also be responsible for this observation (Salsich et al., 2000).

A reduction range of motion between the Cal-Mid and Cal-Met was observed in both diabetic cohorts, which highlight the usefulness of 3DMFM when compared to conventional lower limb models. In both diabetic cohorts these significant changes with respect to the control group occurred predominantly in the transverse plane during FFPOP (Table 3 and Fig. 1). This reduction may be interpreted in light of LJM, more specifically in an impairment of the windlass mechanism. In fact, this mechanism is embodied by a distinct eversion and adduction of the metatarsus with respect to the calcaneus creating a rigid lever for propulsion. However, alterations in elastic properties of the plantar fascia and non-enzymatic glycosylation of other tissues affect the functional behaviour between different segments (Cronin et al., 2010; D'Ambrogi et al., 2005). This altered windlass mechanism has also been pinpointed as causative factor for increased forefoot plantar loading (D'Ambrogi et al., 2005). Reduced transverse plane midfoot and forefoot mobility has also been highlighted as potential evolutional factor of Charcot changes at the midfoot as a result of increased torsional moments about the midfoot (Rao et al., 2010).

The strong correlation reported by Pohl et al. (2007) between rearfoot frontal plane motion (Sha-Cal Inv/Eve) and forefoot transverse plane motion (Cal-Met Add/Abd) was not observed in our study. Defining the aetiology of this discordance is not straightforward; however, potential influencing factors may be the considerable higher age of the Ctrl group in the current study as well as the difference of segmental modelling.

The relatively small sample size can be considered as a limitation of this study, albeit dictated by the specific matching procedure adopted in the study. It should also be acknowledged that diabetes duration was generally higher in the PwDM_NP group, which may have biased the result to a certain extent. It is also appropriate to reflect on the repeatability associated to the Rizzoli_3DMFM. The repeatability of the Rizzoli_3DMFM was recently reported in deformed and non-deformed feet (Deschamps et al., 2012a, 2012b). As a rule of thumb, it can be stated that differences in absolute inter-segment angles should exceed five degrees before it can be considered relevant. For the calculation of RoM during specific subphases, one has to consider a measurement error <2.0° for all 3D rotations (Deschamps et al., 2012a). Experience of therapists may also contribute to the magnitude of the error. In the current study, all measurements were collected by a therapist with five years of experience in gait analysis. In this context, it is also important to reflect on the statistical analysis used in the current study. Adjustment for multiple testing in this study was performed over the set of five test points. This choice can be contested, however, it is a generally accepted approach in explorative studies (Khazzam et al., 2007; Ness et al., 2008). Moreover, a closer look at our data supports this decision, as our significance level ($P < 0.01$) creates a 'benchmark' where it seems that minimally 30% difference in range of motion is being considered as significant (e.g. swing phase).

In summary, the kinematic data of this study indicate important disturbances in foot function in patients with diabetes. Patients with peripheral neuropathy are more affected; however, also non-neuropathic

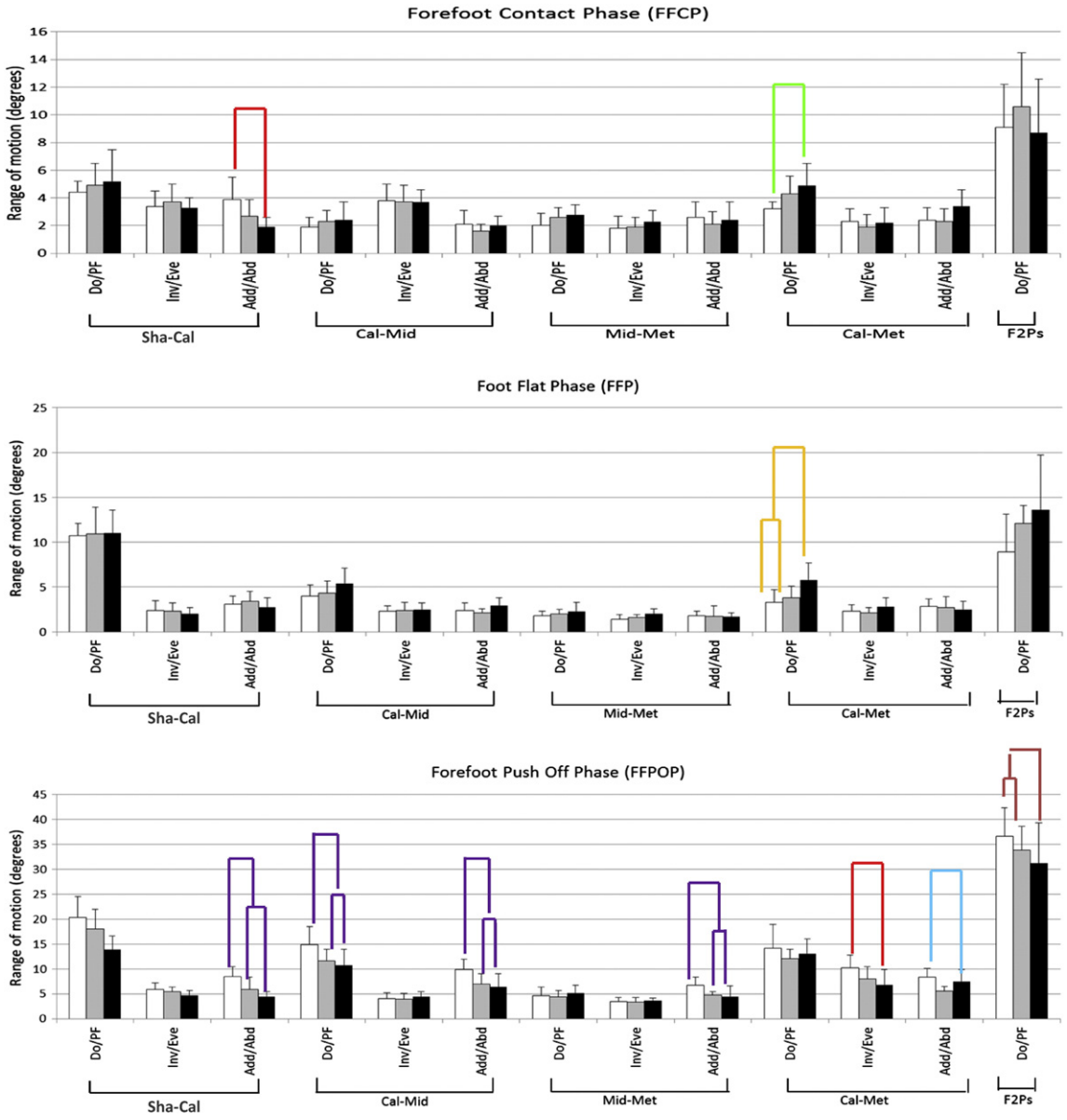


Fig. 1. Range of motion between different segments throughout the three planes and three subphases of stance (Forefoot Contact phase, Foot Flat phase and Forefoot Push Off phase). Significant differences between groups have been colour-coded ($P < 0.01$): —indicates RoM in Ctrl group > PwDM_NP, — indicates RoM in Ctrl group > PwDM_noNP, — indicates RoM in Ctrl group > PwDM_NP and PwDM_noNP, —indicates RoM in Ctrl group & PwDM_noNP > PwDM_NP, —indicates RoM in PwDM_NP > Ctrl group, and —indicates RoM in PwDM_NP > Ctrl group & PwDM_noNP.

individuals show significant alterations. Deficit of somatosensory perception results in a modulation of both, the foot and lower limb kinematics. Of equal importance is to recognize that coupling between segments seems to be affected, which unravels an unexplored area in diabetic foot medicine. In this perspective, it will be important to include other types of data analyses (e.g. vector coding). Future studies should include larger patient cohorts, including female patients, but should also have specific attention for some methodological aspects such as the inclusion of different walking velocities, other functional tasks such as stair ascend and descent as well as including additional matching procedures (e.g. for body mass index). By doing this, it will further enhance insight into the link between neural and mechanical deficits occurring as a consequence of diabetes mellitus (Cronin et al., 2010).

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.clinbiomech.2013.06.008.

Table 4
Mean (S.D.) cross-correlations values for the three groups in the current study. In the right column, published data from Pohl et al. (2007) following an average walking speed of 1.2 m/s^{-1}.

	PwDM_NP (n = 13)	PwDM_noNP (n = 13)	Ctrl (n = 13)	Pohl et al. (2007) (n = 12)
Sha-Cal Inv/Eve_ Sha-Cal Add/Abd	0.53 (0.19)	0.73 (0.23)	0.81 (0.31)	0.46 (0.24)
Sha-Cal Inv/Eve_ Cal-Met Do/PF	−0.4 (0.22)	−0.51 (0.26)	−0.76 (0.18)	−0.79 (0.21)
Sha-Cal Inv/Eve_ Cal-Met Inv/Eve	0.04 (0.14)	−0.42 (0.28)	−0.54 (0.19)	0.33 (0.39)
Sha-Cal Inv/Eve_ Cal-Met Add/Abd	0.68 (0.33)	0.60 (0.29)	0.52 (0.36)	0.91 (0.06)

Conflict of interest

The authors declare that no financial and personal relationships exist which could have influence (bias) their work.

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