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Integrated kinematics–kinetics–plantar pressure data analysis: A useful tool for characterizing diabetic foot biomechanics

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ABSTRACT

The fundamental cause of lower-extremity complications in diabetes is chronic hyperglycemia leading to diabetic foot ulcer pathology. While the relationship between abnormal plantar pressure distribution and plantar ulcers has been widely investigated, little is known about the role of shear stress. Moreover, the mutual relationship among plantar pressure, shear stress, and abnormal kinematics in the etiology of diabetic foot has not been established. This lack of knowledge is determined by the lack of commercially available instruments which allow such a complex analysis. This study aims to develop a method for the simultaneous assessment of kinematics, kinetics, and plantar pressure on foot subareas of diabetic subjects by means of combining three commercial systems. Data were collected during gait on 24 patients (12 controls and 12 diabetic neuropathics) with a motion capture system synchronized with two force plates and two baropodometric systems. A four segment three-dimensional foot kinematics model was adopted for the subsegment angles estimation together with a three segment model for the plantar sub-area definition during gait. The neuropathic group exhibited significantly excessive plantar pressure, ground reaction forces on each direction, and a reduced loading surface on the midfoot subsegment ($p < 0.04$). Furthermore the same subsegment displayed excessive dorsiflexion, external rotation, and eversion ($p < 0.05$). Initial results showed that this methodology may enable a more appropriate characterization of patients at risk of foot ulcerations, and help planning prevention programs.

1. Introduction

Diabetic peripheral neuropathy either reduces or even abolishes the protective sensation; it also induces changes in foot structure and function [1–5]. These conditions predispose to high foot plantar pressure (PP), an important predictive risk factor for the development of diabetic foot ulceration [1,7]. A number of authors found that increased tangential stress is also an important determinant of tissue breakdown in diabetic neuropathic subjects (DPN) [10–13]. However their exact role in the etiology of diabetic foot has not been understood yet. This is mainly due to a lack of commercially available instrument which allows analysis of shear stress distribution on specific foot subareas. In this context some authors further demonstrated that diabetic subjects' gait is characterized by an altered kinematics [9,15–17], which has been recognized also to affect PP [2,8]. PP and kinematics measurement are widely employed to study foot function, the mechanical pathogenesis of foot disease and as a diagnostic and outcome measurement tool for many treatment interventions [1–17]. Rosenbaum et al. demonstrated a close relationship between observed PP and the changes in rearfoot kinematics, suggesting that combined data facilitate a greater understanding of foot function [18]. Thus, the need of a measurement system which can evaluate the effect of abnormal three-dimensional (3D) kinematics and kinetics on PP on specific foot subareas during gait. To the author knowledge two methodologies have been developed since now to estimate both shear stress and PP, even though they do not account for 3D kinematics. One utilizes a piezo-dynamometric integrated platform [19], and the other adopts fiber optic sensors [20]. Both led to encouraging results, although they employed custom made devices in order to measure PP and ground reaction forces (GRFs) which could not be easily transferred into a clinical

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routine gait analysis. Our study outlines our experiences combining 3D motion, GRF, and PP in order to obtain the simultaneous assessment of kinematics, kinetics, and PP on foot subareas of diabetic subjects. This was obtained by means of commercially available systems. A 3D kinematic model already established in our laboratory was used [15]. Such a comprehensive methodology would provide insight into diabetic foot biomechanics and indications for designing prostheses, thus helping preventing plantar ulcers formation.

2. Methods

2.1. Subjects

Subjects were recruited among the patients attending the outpatient Clinic of the Department of Metabolic Disease of the University of Padova (Italy). Inclusion criteria were: type 1 and 2 diabetic subjects with walking ability and no history of ulcers or neurological disorders (apart from neuropathy), orthopedic problems, neurological disorders, lower limb surgery, cardiovascular disease. Control group subjects (CS) were recruited among hospital personnel. On the basis of these criteria 24 patients were examined: 12 CS, 12 DPN. All subjects gave written informed consent. The protocol was approved by the local Ethics Committee of the University Polyclinic of Padova [15,16].

Height and weight (wearing only undergarments, without shoes) were recorded and body mass index (kg/m^2) was calculated.

The neurological evaluation included the assessment of symptoms, and signs compatible with peripheral nerve dysfunction. The Michigan Neuropathy Screening Instrument questionnaire was filled out [23] (classified as DPN if positive for 3 or more out of a total of 15 specified symptoms [24]). The physical examination consisted of: (1) patellar and ankle reflexes, with the patient in the sitting position; (2) assessment of muscle strength by ability to walk on heels, bilateral dorsiflexion/plantarflexion of the feet, flexion/extension of legs, abduction/adduction of both forearms and fingers, all against resistance; (3) sensory testing carried out on the index finger, and on the hallux (pin-prick with a disposable 25 mm/7 mm needle), touch (10 g Semmens Weinstein monofilament, pathologic if no response on 3 out of 10 sites: plantar aspects of the 1st–3rd–5th both digits and metatarsal heads; plantar medial and lateral sides of the midfoot; plantar area of the heel; dorsal aspect of the midfoot [24]) and vibration perception threshold (VPT, 128 MHz tuning fork and Biothesiometer, pathologic if >25 V); (4) pain sensitivity; (5) peripheral nerve conduction test; (6) ankle-to-brachial systolic pressure ratio (Index of Winsor). Cardiovascular autonomic tests (deep-breathing and lean-to-standing tests, Valsalva maneuver, orthostatic hypotension test: abnormality on more than one test) were performed. Subjects underwent foot examination (foot deformities, pre-post surgery ulcers lesions).

HbA1c values from the preceding 10 years were collected. Each patient had at least one ophthalmologic examination, a urinary albumin-to-creatinine ratio measured (0–30 mg/g normal, 30–300 mg/g microalbuminuria, >300 mg/g macroalbuminuria), a carotid artery Doppler ultrasound examination, and a 12-leads electrocardiogram in the three month period preceding the study.

2.2. Experimental set up

Movement analysis was carried on using a 60 Hz 6 cameras stereofotogrammetric system (BTS S.r.l, Padova), 2 force plates (FP4060-10, Bertec Corporation, USA), 2 PP systems (410 × 410 × 0.5 mm, 0.64 cm^2 resolution, 150 Hz, Imagortesi, Piacenza). The signals coming from all systems were temporally and spatially synchronized in post processing thus avoiding the need of modifying either the hardware or the software of the employed systems. The stereophotogrammetric system was used either to perform the automatic footprint subareas subdivision or to compute the 3D foot subsegment kinematics.

2.2.1. Temporal synchronization

Force plates and motion capture system: the synchronization was provided by the motion capture company. PP and force plates: the output of each system was normalized with respect to stance phase of gait. Hence either the variables extracted from the PP system or the ones extracted from the force plates were normalized to 100% of stance phase of gait. Therefore the sample frequency of the systems should not be modified and the method can be transferred to different bands of PP and force plate systems.

2.2.2. Spatial synchronization [11,13,19]

PP and force plates: each PP system was mounted onto each force plates by means of double-sided tape and the spatial alignment of the two platforms was assured by comparing the two center of pressures (COPs). This was performed by defining a coefficient $k = 8$ which measures the relationship between the PP system spatial resolution (each sensors = 8 mm × 8 mm) and the motion capture system one (1 mm). Then by evaluating the mutual relationship between the coordinate of COP of the PP system (COPp) and the coordinates of the COP of the force plates system (COPf). COPp coordinates were determined by means of the following equation:

$$\mathrm{COPp} + \mathrm{O_P} = k \times \mathrm{COPf}$$

O_p: the origin of the PP system in the laboratory reference frame defined by the motion capture system.

2.2.3. 3D foot kinematics

A four segment 3D foot kinematics model was adopted for the subsegment angles estimation during gait (see Fig. 1). The former was previously validated in our laboratory [15]. Skin markers were attached through double sided tape on the anatomical landmarks [15] (Fig. 1). Model segments and joints rotation angles were calculated according to Cardan convention.

2.2.4. Plantar foot subarea definition

A three segment model for the plantar sub-area definition was obtained by means of projecting the anatomical landmarks of the kinematics protocol onto the footprint (Fig. 1) [21,22,25]. The following foot subareas were defined:

- *hindfoot*: the area between the line connecting both the vertical projection of the sustentaculum talii and the throclea peronealis and the vertical projection of calcaneus;
- *midfoot*: the area between the anterior reference line of the hindfoot and the line connecting the vertical projection of the first and fifth metatarsal head;
- *forefoot*: the area between the anterior reference line of the midfoot and the end of the anterior border of the footprint. The plantar surface was compartmentalized so that sensors did not overlap across segments.

2.2.5. Subsegment GRFs

By considering that the vertical (V) component of the GRF and COP coordinates are available from both platforms a global coefficient was calculated as the ratio between the resultants of the V GRF measured by means of the force and pressure platforms, respectively. The former was then applied to correct the absolute force value delivered by the pressure platform [11,13,19]. Thus the resulting compound instrument simultaneously measures, for each sample, the GRF resultant (V and tangential components and COP location) and PP distribution. The two compound platforms were inserted at ground level in the laboratory floor. In order to test if the overlay did not affect the force plates response to GRFs several gait acquisitions were performed in two different conditions: with the force plates free, with the PP system mounted on top of the force plates (see Table 1). Data were compared by means of Student's t-test ($p < 0.05$).

Local sub-segment VGRFs were computed as the summation of the forces measured by each sensor of the pressure platform belonging to the same foot subareas [11]. The anterior–posterior (AP) and medio-lateral (ML) GRFs were calculated assuming they were distributed proportionally to the V GRF [11]. This was performed under the simplified assumption that a foot loaded to half of the body weight can generate half the shear force of a foot with 100% body weight. The same assumption has been previously made in the literature [11], and yielded acceptable results. Of course it is based on some approximations. Even if soft tissues are inelastic, with a nonlinear stress–strain relationship, we adopted the Hookean linear approximation as in Ref. [11]. We considered the tissue to be locally isotropic, and we assumed that the Poisson ratio is a constant in the considered tissue volume. Thus we could calculate the shear forces acting on an elementary foot-to-floor contact area. Finally by assuming that the elementary area corresponds to the area covered by a sensor of the pressure platform located at a distance "d" from the COP [11], we could define three different shear forces acting on the area: fxi, fzi that contribute to the resultant shear forces Fx and Fz respectively, and fMi generated by the free moment applied to COP. By applying the above mentioned assumptions and given:

$$k_i = \frac{\mathrm{fy}_i}{\mathrm{Fy}_i},$$

the following equations can be written as in Ref. [11]:

$$\mathrm{Fx} = \Sigma \mathrm{k_i Fx} - \Sigma |\mathrm{fM_i}| \sin \alpha_i x$$
$$\mathrm{Fz} = \Sigma \mathrm{k_i Fz} - \Sigma |\mathrm{fM_i}| \sin \alpha_i z$$

where x and z are the unit vector of the x and z axes respectively, Fx, Fy, and Fz are the components of the GRF measured by means of the force platform, and fy_i is the elementary V GRF measured by each pressure sensor. GRFs were then normalized to body weight.

2.2.6. PP variables

The elaboration of PP distribution concentrated on the analysis of some meaningful parameters [6,7,22]:

- the COP mean ML/AP excursions and the curve integral were evaluated [16]. Each footprint was compared with the others after rotating each one according to its

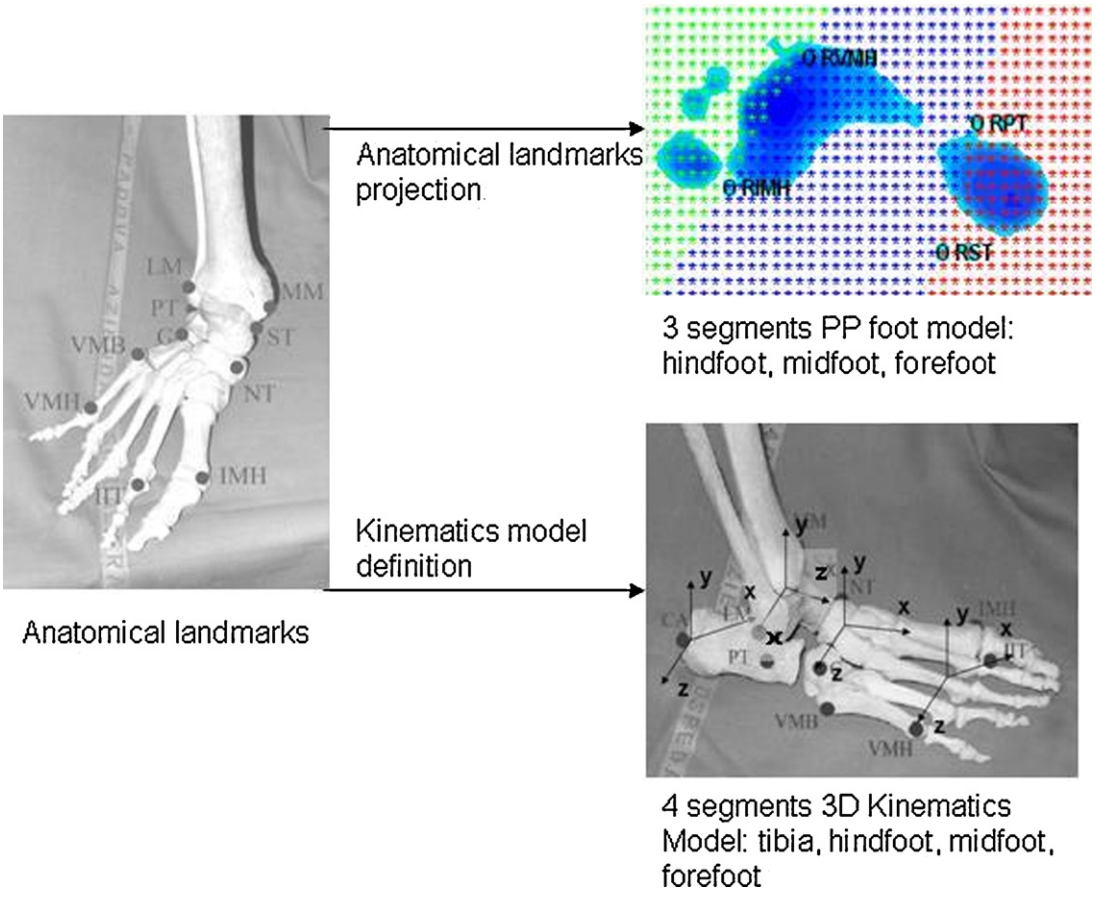

Fig. 1. Details of the four segment three-dimensional (3D) kinematics model [15] and three segment kinetics and plantar pressure (PP) model. Anatomical landmarks definition: sustentaculum talii (ST), throclea peronealis (PT), calcaneus (CA), navicular tuberosity (NT), cuboid (C), fifth metatarsal base (VMB), first (IMH) and fifth (VMH) metatarsal heads, proximal epiphysis of second toe phalanx (IIT). The following model segments and joints relative motion were considered: motion of the hindfoot vs. tibia, motion of the midfoot vs. hindfoot, motion of the forefoot vs. midfoot. Dorsi-plantarflexion, inversion–eversion, and internal–external rotation were considered as the distal segment rotation around respectively: the mediolateral axis of the proximal one (z), its anteroposterior axis (x), the axis obtained as cross product between the other two axes [15]. Foot subareas: hindfoot, midfoot, and forefoot.

Table 1
Comparison between force plate data obtained by one subject walking 10 times over the combined instrument force plate and plantar pressure system (p+p) and the same subject walking 10 times directly over the force plate (p) during the same acquisition session. Mean, standard deviation (SD), maximum (max) and minimum (min) values were reported. Results of paired t-test performed between the two samples of data (p and p+p) were reported in term of P ($P < 0.05$).

	Fx(p+p) [N]	Fx(p) [N]	P	Fy(p+p) [N]	Fy(p) [N]	P	Fz(p+p) [N]	Fz(p) [N]	P
Mean	34.91	33.70	0.5	725.51	715.64	0.7	23.75	29.18	0.2
SD	19.69	18.55		248.58	254.07		70.40	72.46	
Max	61.62	54.47		977.54	971.98		151.42	166.14	
Min	−5.54	−7.50		29.94	34.43		−70.52	−60.83	

Table 2
Clinical and demographic characteristics of diabetic neuropathic group (DPN) and control group (CS). The reported P values indicate the results of the comparison between the DPN and CS groups (one-way ANOVA). A value of $P < 0.05$ was considered statistically significant (P^*).

	DPN		CS		DPN vs CS [P]	
Subjects [no.]	12		12			
Age [years]	62.0 (6.0)		60.3 (5.2)		0.4	
BMI	25.2 (3.2)		24.1 (2.6)		0.4	
Years of disease [years]	26.7 (10.5)		/			
	F	M	F	M		
Sex [no. of subjects]	4	8	2	10	0.2	0.8
Diabetic retinopathy [no. of subjects]	7		/			
Microalbuminuria [no. of subjects]	3		/			
Peripheral vascular disease [no. of subjects]	3		/			

Table 2 (*Continued*)

	DPN	CS	DPN vs CS [*P*]
Autonomic neuropathy [no. of subjects]	1	/	
Type I [no. of subjects]	8	/	
Type II [no. of subjects]	4	/	
HbA_{1c} [%]	8.0 (0.9)	/	
Cavus foot [no. of subjects]	10	7	0.09
Flat foot [no. of subjects]	2	0	0.07
Normal foot [n°of subjects]	0	5	0.006*
Foot deformities [no. of subjects] (claw, allux valgus/rigidus)	8	7	0.3
Plantar callosity	5	2	0.08

Table 3
Subsegments (hindfoot (hf), midfoot (mf), forefoot (ff)), angles (A) [degree (deg)], ground reaction forces (GRF) [% body weight (%BW)], plantar pressure (PP) [kPa], center of pressure (COP) displacement in mediolateral (eML) and anterior–posterior (eAP) direction, COP integral (I) of controls (CS) and diabetic neuropathic subjects (DPN) evaluated during the stance phase of gait. Last column reports a comparison with the literature. Peak or mean values were reported according to the corresponding value in the literature. One-way ANOVA and Student test results expressed in term of *P* value were reported (significant if $P < 0.05$). P represents comparison between DPN and CS.

	CS	DPN	P	Giacomozzi et al., 2006 [6]	
PP [kPa]	Peak	Peak		Peak [N/cm^2]	
wf	584.16	775.78	$P < 0.04$* MS, TS, PS		
hf	427.26	775.78	N.S.	CS 28.9	DPN 30.1
mf	312.32	515.62	$P < 0.04$* MS, TS, PS		
ff	584.16	410.486	N.S.	CS 50.6	DPN 73.5
GRF [%BW]					Uccioli et al., 2001 [11]
wf	ml	6.67	10.17	$P < 0.04$* MS, TS, PS	Peak [%BW] CS 5.0 – DPN 5.2
wf	v	114.38	114.43	$P < 0.04$* PS	Peak [%BW] CS: 108.8 DPN 107.4
wf	ap	18.22	18.25	$P < 0.04$* TS, PS	Peak [%BW] CS 18.5 – DPN 15.3
hf	ml	4.77	5.16	N.S.	Peak: CS 4.4 – DPN 3.3
hf	v	75.26	77.18	N.S.	Peak: CS 93.8 – DPN 87.3
hf	ap	12.69	10.42	N.S.	Peak: CS 15.3 – DPN 15.5
mf	ml	3.64	8.50	$P < 0.04$* MS, PS	
mf	v	71.22	92.51	$P < 0.04$* PS	
mf	ap	10.16	13.11	$P < 0.04$* PS	
ff	ml	4.86	3.90	N.S.	Peak under metatarsal: CS 3.9 – DPN 4.4
ff	v	74.27	82.71	$P < 0.04$* TS, PS	Peak under metatarsal: CS 89.9 – DPN 96.0
ff	ap	13.25	14.94	$P < 0.04$* IC, LS, TS, PS	Peak under metatarsal: CS 13.4 – DPN 12.6
A [deg]		Peak	Peak		Rao et al. [9]
hf	I/E	8.02	23.39	$P < 0.05$* MS, TS, PS	Peak: CS 6.5 – DPN 4.5
hf	Int-ext	20.91	26.53	N.S.	
hf	d-p	11.98	37.98	$P < 0.05$* IC, LS, MS, TS, PS	Peak: CS 6.7 – DPN 5.9
mf	I/E	3.75	22.53	$P < 0.05$* IC, LS, MS	
mf	Int-ext	14.69	18.19	$P < 0.05$* TS, PS	
mf	d-p	16.38	23.83	$P < 0.05$* IC, LS, MS, TS, PS	
ff	I/E	7.41	34.85	$P < 0.05$* IC, LS, MS, TS, PS	
ff	Int-ext	3.66	34.44	$P < 0.05$* IC, LS, MS	
ff	d-p	32.38	20.41	$P < 0.05$* IC, LS, MS, TS, PS	Peak: CS 5.9 – DPN 6.4
COP		Mean	Mean		Giacomozzi 2002 [17] (footprint of size 30 cm x 12 cm)
eAP [% length]		0.89	0.79	0.98	Mean: CS 26.6 – DPN 25.8
eML [% width]		0.41	0.33	0.91	Mean: CS 6.4 – DPN 4.6
I [% length × width]		0.09	0.07	0.14	Mean: CS 38.6 – DPN 25.8

* Int-ext, Internal–external rotation; I/E, inversion–eversion; dp, dorsi-plantarflexion.

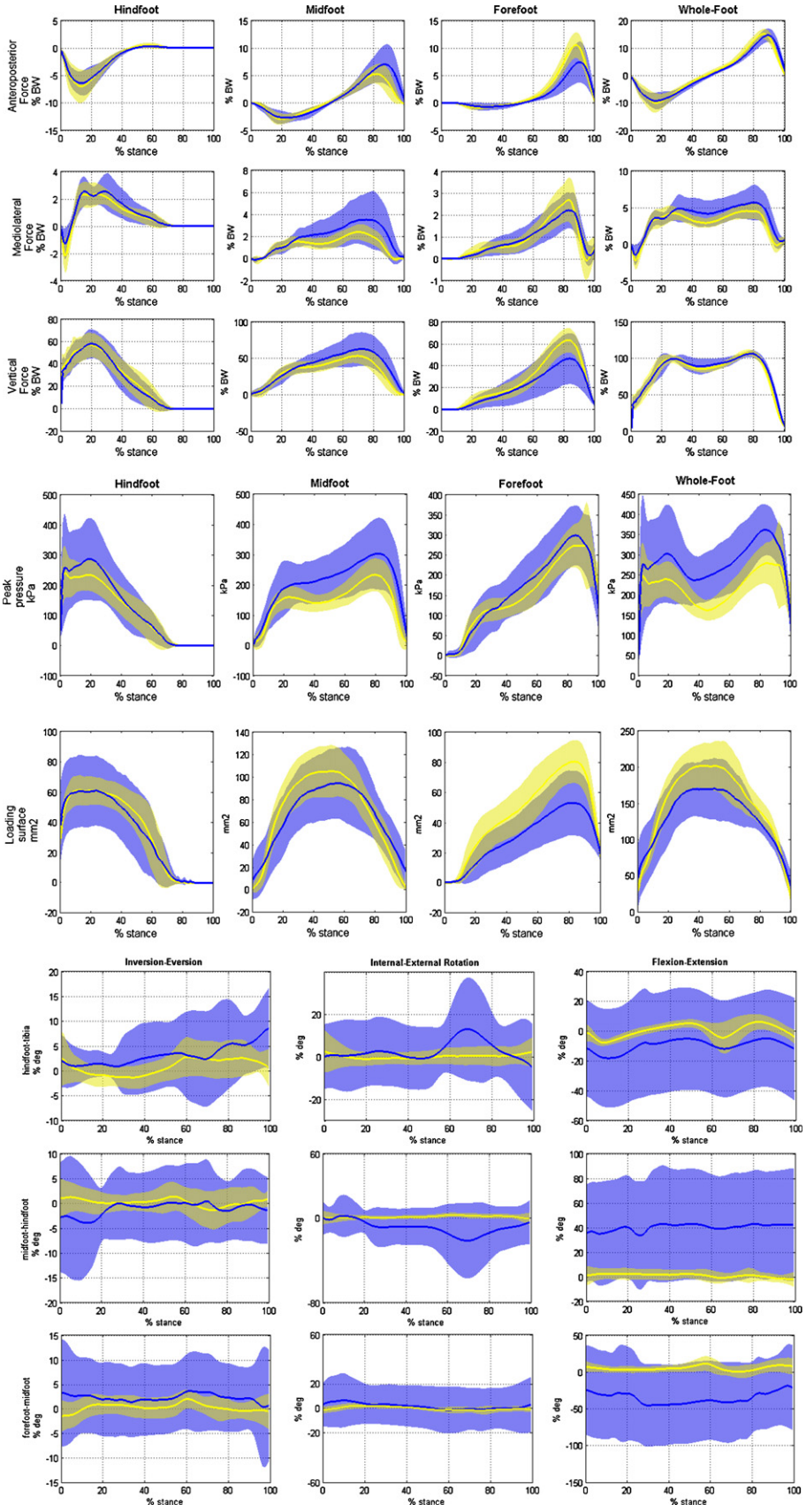

Fig. 2. Mean, standard deviation of subarea forces (top), subarea plantar pressure and subarea loading surface, subsegment rotation angles (bottom), computed on the control group (yellow) over the stance phase of gait, on the diabetic neuropathic group (blue) over the stance phase of gait. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

longitudinal axes. The latter was defined as the line connecting the projection of the 2nd metatarsal head and the calcaneus markers on the footprint. Then the lateral side of the foot was considered as the positive ML direction, and the medial side of the foot as the negative one [16].

- peak and mean pressure curves (PPC and MPC) obtained by linearly interpolating respectively the successive maximum or mean values of pressure during the whole stance phase (normalized to body weight) [6];
- loaded surface curve (LSC) obtained by linearly interpolating the successive medium values of surface covered respectively by the three foot subareas during the whole stance phase (normalized to the foot length).

2.2.7. Motor tasks

- *Static acquisitions* (60 s): Subjects were asked to assume an upright posture with their feet placed with ankles together, toes pointed 30° apart through a guide made of heavy cardboard and the arms along the body [15,26].
- *Gait analysis*: Patients walked at a self-selected speed along a walkway; velocity, stride, and step parameters were calculated. At least three force-plate strikes of each limb (entailing simultaneous acquisition of both GRFs and PP data) were recorded for each patient. For each trial, all angular displacements were plotted over one stance phase.

2.3. Statistical analysis

Each subject's variables were represented with the mean and standard deviation among three representative trials. Intra-class correlation (ICC) was used to aid in selecting which of each subject's representative walking trials were to be included in the computation of the mean; thus the ICC coefficient was calculated for each subject's parameters. Walking trials with an ICC coefficient less than 0.75 (75%) were excluded [16,27].

In order to compare the three populations' data, one-way ANOVA (Tukey–Kramer post hoc comparison, Matlab software, R2008b) and paired *t*-test after evidence of normality (Lilliefor's test) or Kruskal Wallis test were used (considering the variables value on each sample of the stance phase of gait) (Table 2).

The evaluation of the confidence intervals for the observed proportions was performed with the staRt Package of R statistical software.

3. Results

The clinical characteristics of the subjects are reported in Table 2, which shows that all patients were in fair metabolic control. The DPN group had a higher prevalence of both micro- and macrovascular complications. Normative bands have been created with the data of the CS for PP, GRF, and kinematic variables. The data of the DPN were compared with them. Kinematic, kinetic, and PP variables, results of one-way ANOVA together with a comparison with state of the art were reported (Table 3, Fig. 2, Appendix 1). It can be noticed that significant differences were revealed almost on each variables for midfoot and forefoot which are the more critical sites for ulcers formation [1–6,12]. DPN exhibited significantly excessive PP, GRFs on each direction and a reduced LSC on the midfoot subsegment ($p < 0.04$). Furthermore the same subsegment displayed excessive dorsiflexion, external rotation, and eversion ($p < 0.05$).

4. Discussion

This study offers new key findings. The protocol proposed herein allowed the description of the complementary role of kinematics to kinetics, and PP in diabetic subjects gait. Simultaneous kinematics, kinetics, and PP analysis was performed by commercially available systems without applying any additional change to the original systems. The choice of adopting a post processing synchronization solution by means of expressing the GRFs and PP variables in percentage of stance phase of gait represents one of the major advantages of the proposed methodology. This is a valuable capability of the system as the outcome measures are released from the specific system employed for PP and GRFs data acquisition. This is an important characteristic of this study compared to Ref. [19], where a dedicated pressure platform was constructed and the data were transferred to a personal computer through a dedicated board. The system was rigidly fastened to a commercial force platform and synchronized by means of a triggered signal from the PP computer to the motion capture system. The data from the 2 platforms were temporally re-aligned off-line [19]. In our system well established methodologies have been applied for both the automated foot subareas division [25] and the evaluation of local vertical forces [11,19]. The formers were adapted to be used with the 3D kinematics foot model previously developed by the authors [15]. The reported results were comparable to Refs. [18,19] for measurement of GRFs and PP. Differences were probably due to the different foot subareas division as already reported by Giacomozzi et al. [13]. Furthermore, the use of the stereophotogrammetric system either to perform the automatic footprint subareas subdivision or to compute the 3D foot subsegment kinematics represents an important improvement in the methodology proposed in Ref. [19]. Reporting of combined acquisition of PP, kinematics, and kinetics can be also found in the work of MacWilliams [27]. However the latter collected two separate sets of data in order to obtain kinematics, kinetics, and PP data, and modified the camera set up used for the full body gait analysis. At variance, in the present protocol the signals coming from all the systems were collected simultaneously; both right and left gaits were assessed, and the procedure has been successfully included in routine full body gait analysis [20].

It should be further mentioned that evaluating the complementary role of 3D foot subsegment kinematics to PP and GRFs is crucial to study the frequency of abnormal biomechanics and its possible influence on the location and distribution of foot lesions [1,4]. Results (Table 3, Fig. 2) showed the ability of the present methodology to fulfill a similar target. While finding agreement with previous literature [10,11,16,17,28,29], it allowed identification of further alterations occurring in presence of abnormal PP at both hindfoot and midfoot: excessive both V and tangential GRFs, plantarflexion associated with an increment in the internal rotation and inversion, reduced COP's ML displacement.

Finally it should be mentioned that the majority of DPN prevention programs include orthotic devices prescription, and that the formers function to transfer weight away from a painful area and place increased PP where the foot can guarantee a better ambulation. Root et al. [30] assessed that the relationship between biomechanics and orthotic devices is the attempt to change bone and soft tissue alignment of the foot extrinsically, correcting biomechanics which may have led to the functional foot problem. Our methodology could be considered an integral part of these treatment plans.

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Conflict of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2011.12.007.

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