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REDUCTION OF GAIT ABNORMALITIES IN TYPE 2 DIABETIC PATIENTS DUE TO PHYSICAL ACTIVITY: A QUANTITATIVE EVALUATION BASED ON STATISTICAL GAIT ANALYSIS

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The aim of this study is the objective assessment of gait abnormalities in diabetic patients and the quantification of the benefits of physical activity in improving the gait quality. Patients were equipped with foot-switches and knee goniometers and were asked to walk at their natural pace for 2.5 minutes. A statistical gait analysis was performed extracting from hundreds of strides the 'atypical' cycles, i.e. the cycles which do not show the usual sequence of gait phases (heel contact, flat foot contact, push off, swing), the duration of the heel contact phase and the knee kinematics in the sagittal plane. A sample population of 27 non-neuropathic type 2 diabetic patients was examined before and after attending a light-intensity physical activity program that lasted four months. A fuzzy classifier was used to assign a score to the gait abnormalities of each patient in baseline conditions and after the program completion. More than 50% of the subjects reduced significantly their gait abnormalities and, on the average, the most frequent improvements were the reduction of atypical cycles and heel contact duration. Furthermore we found that, in basal conditions, the left side is more affected by gait abnormalities than the right one ($P < 0.003$).

Keywords: Gait analysis; type 2 diabetes; gait abnormalities; foot-switch signal; knee kinematics.

1. Introduction

The World Health Organization (WHO) describes type 2 diabetes as an international epidemic. It estimates that more than 180 million people worldwide have diabetes and that this number is likely to more than double by 2030. Patients with diabetes are at higher risk of experiencing fall-related injuries when walking than healthy controls. However, the underlying mechanism responsible for this is not yet clear.[1]

Diabetes is associated with gait alterations in older adults, but limited information regarding potential explanatory factors for this association exists.[2] More than 50 % of patients who suffered from diabetes mellitus for more than 20 years are affected by neuropathies.[3] Among peripheral neuropathies, the distal symmetric sensorimotor polyneuropathy is the most frequent. In its early stages it causes mainly pain and eventually results in a loss of sensation. The combination of decreased sensation and peripheral arterial disease may lead to foot ulceration and eventual amputation.[4,5]

People with diabetes and peripheral neuropathy are 15 times more likely to fall than it is seen in the same age-matched population with diabetes but no peripheral neuropathy.[6] However, a loss of sensation or proprioception from lower limbs is generally not diagnosed until its consequences cause discomfort to the patient. Since the progression of sensorimotor function degeneration is often relatively slow,[7] it may not be excluded that even at its early stages it causes gait abnormalities that may result in an increased fall risk. In fact, Petrofski et al. (see Ref. 8) found gait impairments in diabetic patients with no sensory loss, and concluded that patients with diabetes present deficits in gait long before objective loss of sensation in the feet.

Considering the potential consequences of falling - skin abrasions, bone fractures, etc. - and the augmented risks of infections and surgery in these patients, it follows that any action that decreases the falling probability is beneficial.

It is well known that physical activity is of paramount importance for diabetic patients and several procedures are available for assessing its benefits from a metabolic point of view.[9,10,11] However, methods for assessing benefits of the physical activity in terms of improved walking ability are not as abundant, and they are usually expensive, time demanding and require dedicated laboratory settings.[12]

Advances in gait analysis allow to perform a comprehensive statistical assessment of gait in a completely operator independent way, by automatically analyzing data relative to hundreds of strides extracted from the same walk.[12,13] This gait test may be performed in schools or hospital corridors, gyms, elderly dwellings, not requiring a dedicated gait analysis laboratory. The gait analysis may be performed at different levels of complexity: in this study we adopted a simplified protocol, using foot-switches and knee goniometers only, thus excluding EMG data. The method allows to evaluate subtle gait abnormalities (not clinically detectable) in less than 15 minutes with a low-cost system.

This paper describes the application of 'statistical gait analysis' to subjects suffering from type 2 diabetes, with no neuropathy/retinopathy complications. The patients, enrolled in a program of physical activity, were tested before the beginning and after the completion of the program. We describe the gait abnormalities observed in these patients, as well as the improvements obtained thanks to the physical activity program. In the analysis we focused on those gait parameters that we think are more relevant in determining the patient's falling propensity.

2. Materials and Methods

2.1 Sample population

We recruited a population of 27 patients, 15 males and 12 females, who were diagnosed with type 2 diabetes and that had no neuropathy/retinopathy complications and/or other neurological or orthopedic disorders affecting gait. The sample population had an age of 66.1 ± 5.8 years (range 55 - 76), a Body Mass Index (BMI) of 30.5 ± 5.0 kg/m^2 (range 22.2 - 43.9), a number of years elapsed from the diagnosis of diabetes of 6.2 ± 5.7 years (range 1 - 25) and a HbA_{1c} of 7.1 ± 1.0 % (range 5.9 - 10.1).

Patients were enrolled in a program of physical activity that lasted four months during which they exercised twice a week for one hour. Each exercise session consisted of: a) 10 minutes of warming up with coordination exercises at reduced velocity and walk at low cadence (45 strides/min.); b) 30 minutes of working out with exercises against gravity involving large muscle groups and movements of the trunk and upper limbs in conjunction with gait; c) 10 minutes of cooling down with light intensity exercises to gradually slow down heart rate; d) 10 minutes of stretching in sit and supine position.

Gait analysis was performed before starting the physical activity program and after its completion. This study was approved by the local ethics committee and all subjects gave their written informed consent before the exams, which was carried out in accordance with the principles of the Helsinki declaration.

2.2 Experimental protocol and set-up

Data were acquired by means of a commercial system providing full software support for performing statistical gait analysis (Step 32, DemItalia, Italy). The patient preparation required approximately 10 minutes. Patients were tested barefooted: thin foot-switches were attached under the heel, the first and the fifth metatarsal heads of each foot. Goniometers were attached, bilaterally, to measure knee joint angles in the sagittal plane. The goniometers used are based on articulated parallelograms and hence do not require the alignment of the potentiometer shaft with the instantaneous center of rotation of the joint. The accuracy obtained with these goniometers is equal to 0.5°. Cables coming from sensors were connected to a small unit (150 mm × 80 mm × 30 mm) tied to the back of the patient through a waist elastic belt. This unit was then connected to a host PC by means of a thin cable (4 mm diameter) 12 m long.

After sensor positioning, patients were asked to walk for a few minutes to get acquainted with the instrumentation. Then patients were instructed to walk at their natural pace continuously back and forth over a 18 m-walkway and signals were recorded for 150 seconds. Hence, for each patient, more than a hundred of strides were available to perform a 'statistical' gait analysis. The turns and the decelerations/ accelerations in proximity of the turns have been removed from the analysis.

Foot-switch and goniometric signals were sampled at 2 kHz and then converted to 12-bit digital format. Foot-switch signals were filtered with an anti-causal anti-bounce filter. Goniometric signals were filtered with an anti-causal low-pass filter with a cut-off frequency of 15 Hz.

2.3 Statistical gait analysis

Since each foot-switch is closed when it touches the floor or opened otherwise, three foot-switches give eight different conditions, i.e. an eight-level basography. However, for the sake of simplicity, these eight conditions are reduced to four (see Fig. 1): (1) Heel contact (H), when only the switch underneath the heel is closed: it approximately

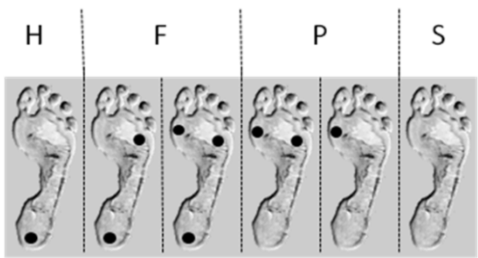

Fig. 1. Phases of the 'typical' gait cycle: heel contact (H), flat foot contact (F), push off (P) and swing (S).

corresponds to the time interval required to complete the heel rocker[13], (2) Flat-foot contact (F), in which the heel switch is closed and, simultaneously, at least one of the metatarsal head switches is also closed: this corresponds to the ankle rocker, (3) Push-off (P) – often referred to as heel raise – in which the heel switch is opened, while at least one of the metatarsal head switches is closed: this corresponds to the forefoot rocker, (4) Swing (S), which corresponds to the phase in which all the switches are opened.

A walking subject may use different gait cycles. In a normal subject, the most frequently observed gait cycle is: Heel contact – Flat foot contact – Push off – Swing (HFPS). However, even in normal subjects, a certain percentage of cycles that are not HFPS may be observed.[12] In the rest of the article we will refer to gait cycles that are not HFPS as ‘atypical cycles’. The system we used to perform the instrumental evaluation relies on an algorithm which allows an automatic segmentation of foot-switch signals. The segmented cycles are then classified in different typologies (HFPS, FPS, PFPS, PS,…) with a misclassification probability lower than 1%.[12] A common atypical cycle is that in which the forefoot, instead of the heel, touches the floor at initial contact (PFPS and PS cycles), but other kinds of atypical cycles may be observed.

We calculated the number of forefoot initial contact cycles and the total number of atypical cycles observed during the walk. Then, the gait phases duration was assessed in ‘normal’ HFPS cycles. We report in this article only the H duration, since it is the most relevant gait phase parameter from a fall-risk point of view.

Fig. 2 shows, in three representative subjects, the knee kinematics (sagittal plane) during gait. The dark-grey curves represent the knee pattern at each single gait cycle, while the light-grey curve represents the average knee pattern during the 150s-walk. Note that the gait cycles corresponding to the turns of the patient (i.e. when the patient changes direction) are automatically removed by the algorithm and are not displayed. Fig. 2a shows a normal knee pattern: notice the high repeatability of the knee curves among different gait cycles. Fig. 2b shows an abnormal knee pattern: a very high amplitude of the first arc of knee flexion can be observed (20°). Notice also the steepness with which the first maximum is reached, corresponding to a very high knee flexion angular velocity (360°/s, instead of the usual 90-130°/s). Fig. 2c presents another example of an abnormal knee pattern: an ‘unstable’ knee in presence of forefoot initial contact (PFPS in this case). Notice the high variability of the curves among different gait cycles.

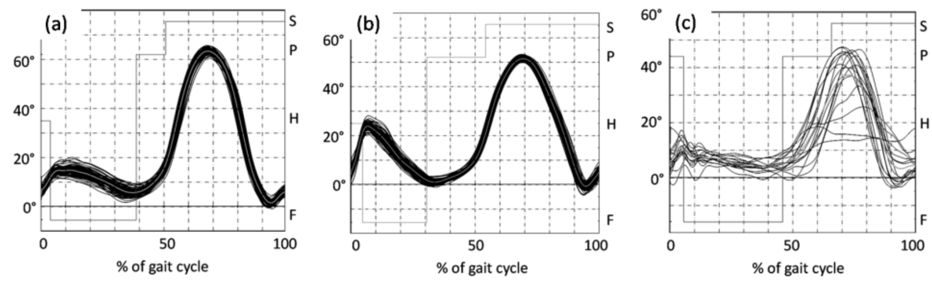

Fig. 2. Sagittal knee joint angles for three representative subjects: single gait cycles observed during the 2.5-minutes’ walk (dark grey curves) and average curve (light grey curve). The vertical axis reports the degrees of knee flexion. The foot-floor contact gait phases are shown superimposed. Fig. 2a – normal pattern; Fig. 2b – abnormal pattern: high (knee flexion) angular velocity during the load acceptance phase; Fig. 2c – abnormal pattern: knee instability in presence of forefoot initial contact cycles (PFPS).

The knee joint curves in the sagittal plane were evaluated for each patient. From these curves we calculated the average values (over the cycles segmented from the same walk) of: the knee dynamic range of motion (ROM), the amplitude of the first arc of knee flexion, the angular velocity of the knee in the weight acceptance phase[14]. We considered also the instability of the knee at load response, in correspondence of forefoot initial contact cycles. Evaluating the dispersion of the curves, we classified the knee as: normal, slightly unstable or unstable.

2.4 Gait abnormality score

In order to score the gait abnormalities of the patients we implemented a fuzzy classifier[15] which, in an automatic and user independent way, assigns each patient to a gait abnormality class. We have considered five output classes for the classifier, each class identifying a certain level of gait abnormality: low, medium-low, medium, medium-high and high. The input membership functions of the classifier were based on the parameters described in Table 1 and will be discussed in the next section. The instability of the knee at load response, in correspondence of forefoot initial contact cycles, was considered as an adjunctive parameter. The classifier was based upon 13 rules, defined with the help of a gait analysis expert. The rules were derived assigning high weights to those parameters that may be related to an increased fall risk. A detailed description of the classifier is beyond the scope of this paper. A validation of the classifier was obtained matching the scores assigned to each patient by the fuzzy classifier with the scores assigned by two gait analysis experts different from the one that defined the rules.

We calculated the number of patients that decreased, did not change or increased the gait abnormality score after the program.

By means of contingency tables of dimension 2x3 and χ^2 statistics we verified the hypothesis of homogeneity of the results obtained (decrease, no change, or increase of gait abnormalities) with respect to gender, age, diabetes duration and metabolic control (HbA_{1c}). The purpose of this analysis was to verify if these characteristics affect the a-priori probability that patients may benefit from attending the program (confidence level: 95%).

We also checked, by means of a contingency table of dimension 2x5, the dependence of patients baseline conditions (low, medium-low, medium, medium-high and high) on laterality (left or right footedness).

3. Results and Discussion

3.1 Evaluation of gait abnormalities

In Table 1 we report the average values, over the population, of the following gait parameters: (1) percentage of forefoot initial contact cycles with respect to the total number of gait cycles, (2) percentage of atypical cycles, (3) heel contact duration, (4) amplitude of the first arc of knee flexion, (5) knee flexion angular velocity during the first rocker, (6) knee dynamic ROM, (7) cadence. These gait parameters were measured before the beginning of the physical activity program and after its completion: values are reported separately for the left and the right lower limb.

Table 1. Gait parameters measured before and after the physical activity program, for the left and the right lower limb, respectively. Data are average values ± standard deviations. Significant differences are displayed with an asterisk: $^{*}P < 0.05$.

Gait parameters	Left			Right		
	Before	After	*P*	Before	After	*P*
Forefoot initial contact cycles (percentage frequency)	3.8 ± 6.2%	3.4 ± 3.2%		3.5 ± 4.0%	3.7 ± 4.0%	
Atypical cycles (percentage frequency)	9.9 ± 10.9%	4.8 ± 4.0%	*	7.7 ± 5.1%	4.4 ± 3.2%	*
H: heel contact duration (% of gait cycle)	8.0 ± 5.1%	4.9 ± 1.4%	*	6.3 ± 3.1%	4.9 ± 1.3%	*
Amplitude of 1st arc of knee flexion (degrees)	8.6 ± 3.3°	8.9 ± 3.5°		7.6 ± 3.4°	8.8 ± 3.3°	
Knee flexion angular velocity (degree/s)	122 ± 46°/s	118 ± 45°/s		110 ± 50°/s	121 ± 54°/s	
Knee dynamic ROM (degrees)	48.8 ± 7.7°	51.5 ± 6.8°		47.3 ± 7.1°	49.0 ± 7.2°	
Cadence (strides/min)[a]	54.8 ± 3.6	55.9 ± 4.2				

[a]Average value between the left and the right side.

The number of atypical cycles significantly decreased after the physical activity program completion: using a Student's paired *t*-test to verify the hypothesis that atypical cycles decreased, we obtained $P = 0.028$ for the left lower limb and $P = 0.003$ for the right one. The heel contact duration also significantly decreased: using the same test we obtained P = 0.003 and P = 0.021 for the left and the right lower limb, respectively.

The results over the population show that the atypical cycles and the heel contact duration (H) are the most relevant (stand-alone) parameters highlighting the patients improvements (normality range for atypical cycles: 0-5%; normality range for H: 3-7 % of the gait cycle). However, it may be interesting to investigate how each single patient responds to the program of physical activity, assigning a 'gait abnormality score' that takes into account all the considered parameters (including the instability of the knee) and their possible interrelations.

3.2 Evaluation of the gait abnormality score

The level of gait abnormalities of the patients - in baseline conditions and after attending the program of physical activity - was evaluated by means of the fuzzy classifier. Fig. 3 shows the bar graph of the gait abnormality score of the population before the beginning and after the completion of the program. It can be observed that the level of gait abnormalities significantly decreases after the physical activity. On the left lower limb, the most evident effect is the increment of subjects populating the 'low' class (from 6 to 17) and the reduction of the 'medium-low' class (from 16 to 7). On the right lower limb a decrease in the gait abnormalities is also observed, but it is less remarkable. In summary, more than a half of patients decreased the gait abnormality score on the left lower limb, while only one third of them reduced it on the right.

We observed worse baseline conditions on the left lower limb, i.e. higher levels of gait abnormalities (see Fig. 3): after the physical activity the improvements are more visible on this side. In fact, more evident improvements are observed when baseline conditions are more severe.

We found that the decrement in gait abnormality does not depend on BMI ($P > 0.5$), HbA_{1c} ($P > 0.3$), gender ($P > 0.1$) and age ($P > 0.07$). On the contrary, we found a statistically significant dependence of the results obtained with respect to the time elapsed since the onset of diabetes ($P < 0.03$): patients who have been diagnosed with diabetes for less than 5 years obtain greater benefits from the physical activity than patients who suffered from diabetes for a longer period of time. For what concerns the dependence of patients baseline conditions on laterality, we found that the left lower limb shows worse baseline conditions than the right one ($p < 0.003$).

The importance of laterality on diabetes patients was outlined by Coxon et al. (see Ref. 16) who reported that the excess of right-sided amputations in patients with diabetes might be related to right/left sided dominance (i.e. right or left footedness) since this might be expected to determine which foot is used most for initiating or stopping movement. It was also suggested that a dominant foot might be subjected to greater shearing or mechanical stress or might be more susceptible to injury by accident.

Coren reports that approximately 88% of females and 83% of males are right-footed.[17] Since the right side is predominant in the majority of the subjects, and hence it is used for more complex tasks, it is likely to be more trained, and, as a consequence, it may be more lately affected by gait abnormalities. This observation can explain our findings about lateralization.

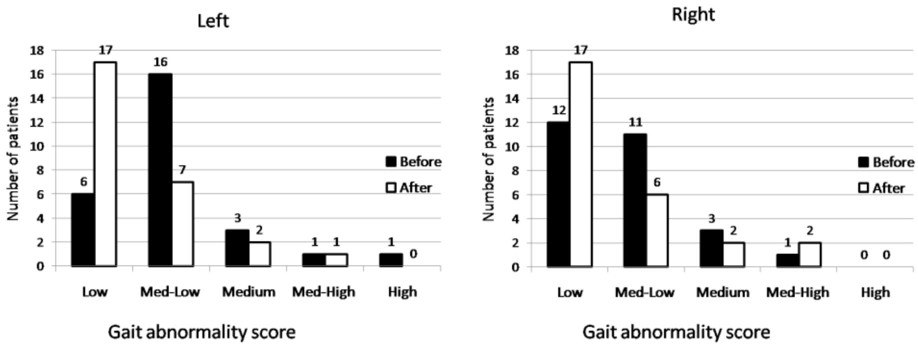

Fig. 3. Bar graph of gait abnormality score before and after the physical activity program, for the left and the right lower limb.

4. Conclusions

We analyzed a population of non-neuropathic type 2 diabetic patients, enrolled in a program of physical activity. By means of statistical gait analysis and the use of a fuzzy classifier we demonstrated that it is possible to quantitatively assess the gait abnormalities of the patients, and, consequently, evaluate the benefit they gained by attending the program. The patients initially showed gait abnormalities that statistical gait analysis was able to evidence.

Our results demonstrate that the majority of the patients decreased their gait abnormality score after the completion of the physical activity program. We believe this is an interesting result since it is observed in diabetic patient with no neuropathy, while gait abnormalities are usually studied in patients with peripheral neuropathy.

Moreover, since we found that patients who have been diagnosed with diabetes for less than 5 years are more likely to benefit from a light-intensity physical activity program, we believe that it is important to evaluate patient gait abnormalities right after the diabetes diagnosis, even in absence of clinical signs of neuropathy. Therefore it is important an early enrollment of these patients in physical activity programs, not only for blood glucose control, but also to reduce gait abnormalities and possibly decrease the risk of fall.

Finally, our data show that before attending the program the left lower limb was more affected than the right one, possibly due to lower limb side dominance. We also found that the improvements on the left side are greater than those observed on the right.

In conclusion, we believe that statistical gait analysis is an important tool in the management of diabetic patients to objectively assess gait abnormalities before and after a physical activity program and hence to document the improvements obtained in the gait quality.

References

1. Allet L, Armand S, Golay A, Monnin D, de Bie RA, de Bruin ED, Gait characteristics of diabetic patients: a systematic review, *Diabetes Metab Res Rev* **24**(3):173–191, 2008.
2. Brach JS, Talkowski JB, Strotmeyer ES and Newman AB, Diabetes Mellitus and Gait Dysfunction: Possible Explanatory Factors, *Phys Ther* **88**(11):1365–1374, 2008.
3. Boulton JM, Management of Diabetic Peripheral Neuropathy, *Clin Diabetes* **23**:9–15, 2005.
4. Duby JJ, Campbell RK, Setter SM, White JR, Rasmussen KA, Diabetic Neuropathy: An Intensive Review, *Am J Health-Syst Pharm* **61**(2):160–176, 2004.
5. Acharya UR, Rahman MA, Aziz Z, Tan, PH, Ng EYK, Yu W, Computer based identification of plantar pressure in type 2 diabetes subjects with and without neuropathy, *Journal of Mechanics in Medicine and Biology*, **8**(3):363–375, 2008.
6. Cavanagh PR, Derr JA, Ulbrecht JS, Maser RE, Orchard TJ, Problems with gait and posture in neuropathic patients with insulin-dependent diabetes mellitus, *Diabet Med* **9**(5):469–474, 1992.
7. Dingwell JB, Cavanagh PR. Increased variability of continuous overground walking in neuropathic patients is only indirectly related to sensory loss, *Gait Posture* **14**:1–10, 2001.
8. Petrofsky J, Lee S and Bweir S, Gait characteristics in people with type 2 diabetes mellitus, *Euro J Appl Physiol* **93**(5-6):640–647, 2005.
9. Knowler WC, Barrett-Connor E, Fowler SE, Hamman RF, Lachin JM, Walker EA, Nathan DM; Diabetes Prevention Program Research Group, Reduction in the incidence of type 2 diabetes with lifestyle intervention or metformin, *N Engl J Med* **346**:393–403, 2002.
10. Boulé NG, Haddad E, Kenny GP, Wells GA, Sigal RJ, Effects of Exercise on Glycemic Control and Body Mass in Type 2 Diabetes Mellitus, *JAMA* **286**:1218–1227, 2001.
11. Acharya UR, Ghista DN, Nergui M, Chattopadhyay S, Ng EYK, Sree VS, Tong JWK, Tan JH, Loh KM, Suri JS, Diabetes mellitus: enquiry into its medical aspects and bioengineering of its monitoring and regulation, *JMMB* **12**(1):1230001–42, 2012**.**
12. Agostini V, Knaflitz M, Statistical gait analysis, in: Acharya, J.R., Molinari F, Tamura T, Naidu DS, Suri JS, (eds.), in *Distributed Diagnosis and Home Healthcare (D2H2)*, Stevenson Ranch, American Scientific Publishers, pp. 99–121, 2012.
13. Agostini V, Nascimbeni A, Gaffuri A, Imazio P, Benedetti MG, Knaflitz M, Normative EMG activation patterns of school-age children during gait, *Gait Posture* **32**, 285–289, 2010.
14. Perry J, *Gait Analysis: Normal and Pathological Function*, Slack Inc, Thorofare (NJ), 1992.
15. Zimmermann HJ, *Fuzzy set theory and its application*, fourth edition, Kluwer Academic Publisher, Boston, 2001.
16. Coxon JP and Gallen IW, Laterality of lower limb amputation in diabetic patients: retrospective audit. *BMJ* **318**:367–367, 1999.
17. Coren S, The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: norms for young adults, *Bull Psychon Soc* **31**:1–3, 1993.