ELSEVIER

Journal of Electromyography and Kinesiology 14 (2004) 275–281

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

www.elsevier.com/locate/jelekin

Footprint analysis of gait using a pressure sensor system

Ekaterina B. Titianova [a], Plamen S. Mateev [b], Ina M. Tarkka [c,*]

[a] Specialized University Hospital of Neurology and Psychiatry 'St. Naum', Department of Neurology, Sofia, Bulgaria
[b] Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, Bulgaria
[c] Brain Research and Rehabilitation Center Neuron, Kuopio 71130, Finland

Received 31 January 2003; received in revised form 3 June 2003; accepted 6 June 2003

Abstract

The purpose of this study was to investigate if the detailed pressure data of the footprints of normal gait add essential information to the spatio-temporal variables of gait. The gait of 62 healthy adult subjects was investigated using GAITRite® pressure sensor system. Each footprint was divided into 12 equal trapezoids and after that the hindfoot, midfoot and forefoot analysis was developed. A typical activation pattern of the sensors with two peaks of active area and peak pressure distribution during normal walking was obtained. The first peak reflected the heel strike, and the second peak reflected push-off at the end of the stance phase. The lowest pressure values were in the midfoot, where the lateral part of the foot activated sensors more than the medial part. The footprint patterns of right and left legs were symmetrical and corresponded with the symmetry found in the spatio-temporal variables of gait. The variability for the active area and the peak pressure were more pronounced for the lateral part of the midfoot and a smaller variation was seen in areas with concentrated observations (e.g. 1st, 2nd and 5th lateral trapezoids). Increasing active area in the forefoot was associated with decreasing pressure sensor activity in the midfoot. The footprint patterns identified the symmetry between the legs and at the same time revealed the velocity performance.

Keywords: Human; Walking; Walkway; Step; Functional ambulation profile

1. Introduction

Information about the pressure distribution and active foot contact area during walking is considered to be important for the practice of neurology and physical medicine. It is known that high pressure in the forefoot area occurs during the push-off phase of gait when the heel leaves the ground, and the entire body weight is borne on the forefoot and toe [22]. Abnormally high plantar pressure in people with sensory deficits of the lower limbs has been linked with ulcer foot complications [1]. Reduction of peak plantar pressure on the forefoot during walking has became a primary focus of prevention and treatment of this condition [10].

Various methods have been used for estimation of gait parameters, however, only few can provide reliable information about foot pressure distribution during gait. Most of the techniques are labour-intensive, time consuming or otherwise insufficient for collecting reliable data [4]. Recent technology has resulted in flexible and portable walkways with embedded pressure sensitive sensors. The advantage of a walkway is evident when transferring objective measures of gait to clinical practice since, for example, neurologically impaired patients tolerate poorly lengthy preparations and many attached cords for recording purposes. Clearly the information obtained with a walkway is not as complete as that obtained with 3-D motion analysis. The pressure sensor system records the location of the foot activated sensors and the time of their activation/deactivation. It provides the spatial and temporal variables of gait along with a dynamic pressure mapping of each footprint during walking [11,13].

The purpose of the present study was to investigate if detailed pressure data of footprints of gait add essential information to the spatio-temporal gait variables. The footprint parameters (peak pressure, peak pressure time,

* Corresponding author. Tel.: +358-17-460-281; fax: +358-17-460-200.
E-mail address: Ina.Tarkka@neuron.fi (I.M. Tarkka).

1050-6411/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S1050-6411(03)00077-4

sectional integrated pressure over time ($P \times t$) and active area) measured by a pressure sensor system were analysed and their relationship with Functional Ambulation Profile (FAP, a score calculated by the manufacturer) and the spatio-temporal variables of a normal gait were evaluated.

2. Methods

2.1. Subjects

Sixty-two clinically healthy subjects (21 men and 41 women, mean age 41.4 ± 11.0 years, range 21–61 years) were included in the study. All of them were volunteers with a normal physical development, free of medication and without a history of previous gait disorders. Body height and weight measures were recorded at the time of the investigation (Table 1). Gender subgroups were of similar age, however they were significantly different in relation to their height, weight and lower limb length. The participants gave informed consent prior to the study. They were engaged in a small training session before recording.

2.2. Recording methods

All gait measurements were performed with a portable GAITRite® system (SMS Technologies, UK). The company manufacturing this equipment or the distributor were not involved in any way in this study. This system consists of an electronic walkway of 4.57 m with an active area of 3.66 × 0.61 m, where the sensor pads are encapsulated. 13,824 sensors, each 1 cm in diameter, are arranged in a 48 × 288 grid pattern. The system continuously scans the sensors, provides information about the geometry of the footprints in 2-D space and gives a dynamic pressure mapping during walking by recording the location of activated sensors and the time of sensor activation/deactivation. At least one complete stride for each side inside the walkway is required to complete the computation. Measurements of the spatial and temporal gait variables are based on the geometric centers of heels for each of the 3 consecutive footprints (Fig. 1) [6].

The subjects were asked to walk twice across the walkway without shoes with their self-selected speed within the range of cadence (steps/min) from 103 to 140. The average of both performances was analysed. The walking distance (cm) and the ambulation time (s) were obtained from the heel centers of the first and last footprints. The step length (cm) was measured from the geometrical heel center of the current footprint to the same of the previous footprint on the opposite foot, and the stride length (cm) from the line of progression between the heel points of two consecutive footprints of the same foot. The step time (s) elapsed from the first contact of one foot to the first contact of the opposite foot, the gait cycle time (s) elapsed from the time between the first contacts of two consecutive footprints of the same foot. The stance time (s) was measured between the first and last contact of the same footprint and the swing time (s) between the last contact of the current footprint and the first contact of the next footprint of the same foot. The walking velocity (cm/s) was obtained after dividing the recorded distance by the ambulation time. Additionally, the lower limb length (LL) was measured (cm) manually separately for the left and the right extremity from the greater trochanter to the floor, the line of measurements bisecting the lateral malleolus. The velocity was divided by the average LL to obtain a normalized velocity (LL/s). The step/extremity ratio (SL/LL) was evaluated dividing the step length by the LL of the same leg. Heel to heel (HH) base of support (cm) was the horizontal distance from the heel point of one footfall to the line of progression of the opposite foot [6]. The measurement of toe in/ toe out angle (degrees) is explained in Fig. 1.

According to the recording system, the footprint was divided into 12 trapezoids, 6 for the lateral part and 6 for the medial part. Each trapezoid, non-square, includes a specific number of sensors and the order for assigning sensor activation is heel-to-toe. To simplify the manufacturer's concept of six lateral and six medial parts of a footprint, we divided the footprint into three segments: hindfoot, midfoot and forefoot. Each of them includes two trapezoids from the lateral and two from the medial

Table 1
Subject description

Parameters	Whole group $n = 62$	Men $n = 21$	Women $n = 41$
Age (years)	41.4±11.0	41.9±11.6	41.2±10.9
Height (m)	1,70±0,09	1,79±0,06	1,65±0,05***
Weight (kg)	71.6±11.6	81.1±10.3	66.7±8.9***
Leg length (cm)	86.9±4.8	90.4±3.6	85.1±4.4***

***$p < 0.001$—significance between men and women.

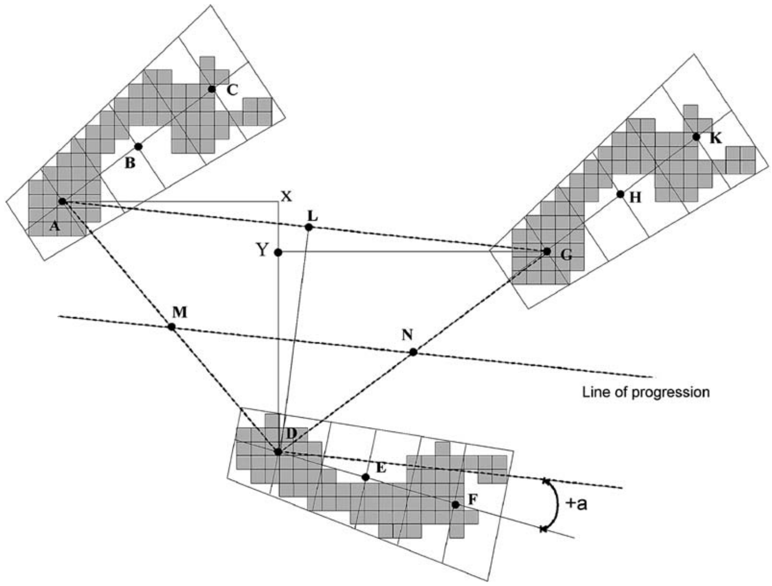

Fig. 1. Spatio-temporal measurements of GAITRite® system are based on three footprints. The grey squares represent the pressure sensors and the trapezoids (non-squares) of each foot are the technical basis for footprint calculations. Points A, D and G are the geometric centers of the heel for each footprint. The line AG represents the stride length of the left foot, the line AX—the step length of the right foot, the line YG—the step length of the second left footprint, the line DL shows the base of support. The line of progression connects midpoint M of the line AD with the midpoint N of the line DG. Toe-in/out angle is between the geometric mid-line of the right footprint and the line of progression. The angle is zero if the geometric mid-line of the footprint is parallel to the line of progression; positive when the mid-line of the footprint is outside the line of progression; and negative if inside the line of progression.

part. The following parameters were evaluated: segmental integrated pressure over time ($P*t$) (expressed as a percent of the overall integrated pressure over time), peak time (s) (first time point of each trapezoid when one or more sensors within a segment is at the maximum switching level), active area (expressed as a percent of the sum of the active sensors within one segment) and peak pressure (the maximum switching level expressed as a percent of the overall maximum switching level at the peak time in a segment).

The Functional Ambulation Profile (FAP) scores, calculated by the system, were compared with the obtained spatio-temporal gait parameters. For each limb, the SL/LL ratio, step time and normalized velocity are compared on a model of regression lines to determine their deviations from normal. This part constitutes 44% of the total FAP score. Degree of asymmetry represents 8% of the score and the base of support also represents 8% and the use of assisting devices represents 5 %. The final score is derived subtracting points from a maximum score of 100. Deductions are made in the formula for the use of assisting devices and ambulatory aids, excessive base of support, degree of asymmetry and deviations of left and right step functions. The manufacturer offers that the FAP score from 98 to 100 is obtained at ordinary speed when step extremity ratios and step times are symmetrical and a dynamic base of support is less than 10 cm [6,8].

Footprint data, spatio-temporal variables of gait and FAP scores were obtained from all subjects. In order to avoid any effects of acceleration and deceleration phases of walking, the first and the last footprints were not included in the pressure analysis.

Paired t-test was applied to compare the gait variables between the legs. Non-parametric confidence intervals were used to compare the footprint parameters. Pearson correlation and linear regression analysis were also performed. A canonical correlation was applied in order to search for a possible relationship between anthropological variables (6), temporal gait variables (21), footprint peak area variables (24), footprint peak time variables (24), footprint peak pressure variables (24) and footprint $P*t$ variables (24). The software system Statistica [18] was used in the computation.

3. Results

3.1. Footprint analysis

Activation and pressure information from each trapezoid (see Fig. 1) was used and as an example the peak time of activation is presented in Table 2. A strict symmetry between the legs, corresponding to peak time in Table 2, was found in all footprint variables. The midpoint of each footprint showed the lowest percent $P*t$, active area activation and peak pressure and the three segments (hindfoot, midfoot and forefoot) differed statistically significantly (Fig. 2). Increasing active area in

Table 2
Peak time of pressure sensor activation in footprints partitioned into 12 trapezoids of normal gait of 62 healthy adult subjects (R = right, L = left)

Parameters	Peak time (s)	
	R	L
Medial footprint		
1 trapezoid	0.07±0.05	0.06±0.04
2 trapezoid	0.12±0.03	0.13±0.02
3 trapezoid	0.03±0.06	0.05±0.08
4 trapezoid	0.25±0.14	0.20±0.15
5 trapezoid	0.44±0.04	0.44±0.04
6 trapezoid	0.49±0.05	0.49±0.05
Lateral footprint		
1 trapezoid	0.06±0.05	0.06±0.04
2 trapezoid	0.13±0.03	0.14±0.04
3 trapezoid	0.16±0.09	0.18±0.10
4 trapezoid	0.33±0.08	0.32±0.09
5 trapezoid	0.43±0.05	0.44±0.05
6 trapezoid	0.43±0.11	0.45±0.13

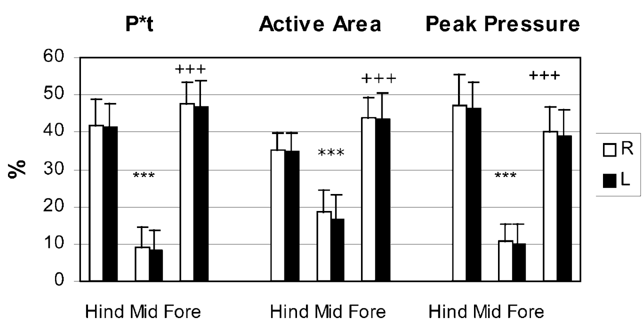

Fig. 2. The distribution of the integrated pressure over time ($P*t$), the active area and the peak pressure between the hindfoot (Hind), midfoot (Mid) and forefoot (Fore). *** $p < 0.001$—significance between midfoot parameters and those of other two segments; +++ $p < 0.001$—significance between the values of the hindfoot and forefoot on both sides.

the forefoot was associated with decreasing peak pressure in the same segment.

When analysing each trapezoid, the integrated pressure over time, peak time, active area and peak pressure distribution differed between the medial and the lateral parts of the footprint. The peak time increased from hindfoot to forefoot for the lateral part of the footprint while for the medial part more variation was observed. The non-parametric confidence intervals (5- and 95-percentiles) showed higher peak time variability in the midfoot and the lateral forefoot (corresponding to the small toes) compared to hindfoot with more compact observations. Medial part of the footprint appeared to have lowest values of $P*t$, active area and peak pressure in the third and fourth trapezoids, while in the same trapezoids the active area of the lateral part of the footprint was significantly larger with higher variability. Trapezoid integrated pressure over time and the peak pressure showed corresponding differences among the trapezoids with lowest values in the midfoot.

3.2. Spatial and temporal variables of gait

Spatial and temporal gait variables are shown in Table 3. Although men were significantly taller and heavier and had longer lower limb and step lengths than women, no significant difference in the step/extremity ratio was found between the sexes. The duration of the step time was significantly longer in men than in women, however the swing and stance percent distributions of one gait cycle and the normalized velocity did not show gender difference. Walking speeds ranged from 96.4 cm/s to 206.2 cm/s. Men had lower cadence than women. The taller the subject the higher was the comfortable speed ($r = 0.36$, $p < 0.01$). The toe in/toe out angle varied for both sexes but there was a greater angle in men.

The symmetrical pattern of walking was present in all subjects regardless of gender, age, height or body weight (see Table 3). Spatial and temporal parameters of gait closely related to the speed of walking. With increasing velocity an increase e.g. in cadence ($r = 0.71$, $p < 0.001$), step length ($r = 0.82$), (left = L), $r = 0.85$ (right = R), $p < 0.001$) and stride length ($r = 0.84$ (L), $r = 0.86$ (R), $p < 0.001$) was observed. These changes were accompanied by decreased e.g. step time, cycle time, swing time, stance time ($r = -0.77$ (L), $r = -0.72$ (R), $p < 0.001$) and double support duration ($r = -0.72$ (L), $r = -0.71$ (R), $p < 0.001$).

Table 3
Spatial and temporal gait variables in 62 healthy subjects (Mean ± SD)

Parameters	R	L
Step time (s)	0.50±0.04	0.50±0.04
Step length (cm)	74.3±7.4	73.9±7.3
Step extremity ratio (SL/LL)	0.85±0.07	0.85±0.07
Cycle time (s)	1.01±0.07	1.01±0.07
Stride length (cm)	148.6±14.9	149.1±14.4
HH base support (cm)	9.29±3.05	9.32±3.05
Swing % of cycle	42.80±1.60	42.79±1.61
Swing time (s)	0.43±0.02	0.43±0.03
Stance % of cycle	57.20±1.60	57.22±1.61
Stance time (s)	0.58±0.05	0.57±0.05
Double support % of cycle	13.14±3.28	13.22±2.88
Double support time (s)	0.13±0.04	0.13±0.03
Toe in/toe out (degrees)	9.46±6.36	8.28±4.96
Step length differential (s)	2.07±1.73	
Step time differential (s)	0.02±0.02	
Cadence (step/min)	120.8±8.3	
Velocity (cm/s)	149.5±19.6	
Mean normalised velocity (LL/s)	1.72±0.21	
FAP (scores)	90.1±9.1	

L = left side, R = right side.

3.3. Functional ambulation profile analysis

The gait velocities ranged from 96.4 cm/s to 206.2 cm/s resulting in a wide variety of FAP scores (56–100). FAP correlated positively with the temporal gait parameters (such as step time and swing time). An inverse relationship was found between the FAP scores and the cadence ($r = -0.75$, $p < 0.001$). FAP scores decreased with increasing mean normalized velocity ($r = -0.94$, $p < 0.001$) and gait velocity ($r = -0.82$, $p < 0.001$).

3.4. Relationship between footprint parameters, temporal variables of gait and FAP scores

In the footprints, increasing active area of the hindfoot and forefoot was related to increasing peak pressure of the same segments and at the same time decreasing peak pressure in the midfoot. The increase in gait velocity and cadence decreased the peak time in the hindfoot and forefoot and increased the peak pressure in the forefoot ($r = 0.31$ (R, L), $p < 0.05$). Peak pressure in the forefoot also tended to increase when the swing ($r = -0.30$ (R), $r = -0.26$ (L), $p < 0.05$) and stance duration ($r = -0.35$ (R), $r = -0.37$ (L), $p < 0.01$) of gait cycle decreased (Fig. 3).

The peak time of the footprint segments were closely related to the temporal variables of gait –step time, cycle time, stance time, swing time and double support time. FAP scores increased with increasing peak time.

When looking for the effect of age in our healthy subjects no correlation with the footprint parameters, gait variables or FAP was found. Only the base of support tended to decrease with age ($r = -0.31$ (L), $r = -0.28$ (R), $p < 0.05$). The increase in body weight increased the peak pressure of the hindfoot ($r = 0.37$ (R), $p < 0.01$, ($r = 0.28$ (L), $p < 0.05$) and the active area of the midfoot ($r = 0.41$ (R), $p < 0.001$, $r = 0.35$ (L), $p < 0,01$), while the active area of the hindfoot and forefoot decreased. The canonical correlation analysis also supported the above findings (see Table 4).

4. Discussion

It is commonly observed and shown by several recording methods that freely walking people choose a certain velocity and gait pattern. At any given speed people can vary their walking pattern by changing the step length and the step frequency [14] tending to walk with optimal velocity and cadence with minimal energy expenditure [5,9].

The present study analyses footprint patterns of normal gait with a relatively new methodology. The validity and reliability of the GAITRite® system has been previously evaluated and reported by McDonough et al. [11]. Therefore, the emphasis of our study was the foot-

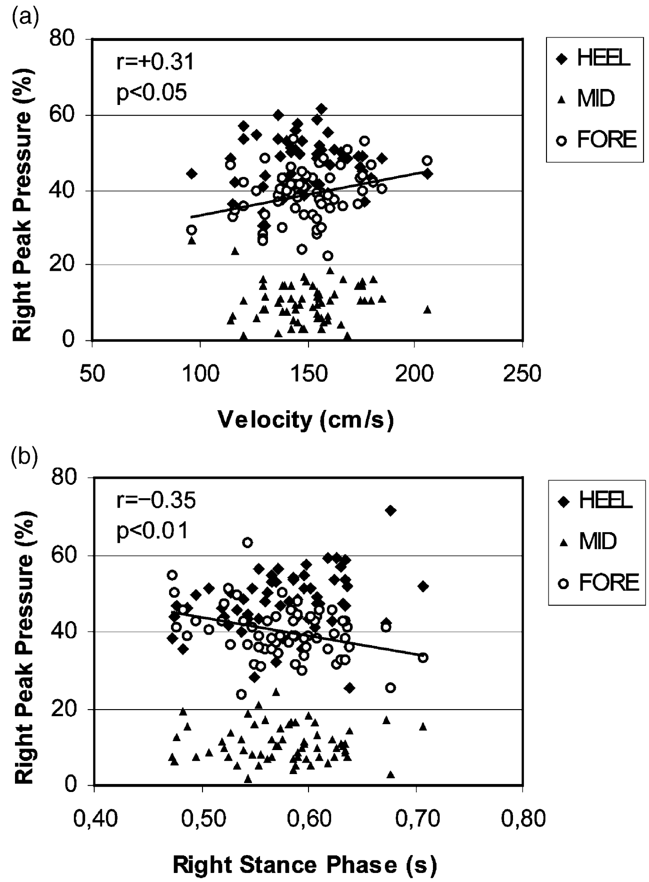

Fig. 3. Linear regression between footprint pressure information and spatio-temporal gait data. Regression between right footprint peak pressure data (including hindfoot “Heel”, midfoot “Mid” and forefoot “Fore”) and gait velocity shown on the top and stance duration shown on the bottom. Peak pressure produced by forefoot was higher when gait velocity increased and it decreased with decreasing gait velocity (shown by the duration of stance phase).

print information as pressure activation/deactivation parameters are not among the traditional measures of gait. Although the pressure sensor activity varied between the footprint segments, a typical pattern with two peaks of active area and peak pressure distribution during normal walking was obtained. The first peak reflected the heel strike, and the second peak reflected push-off at the end of the stance phase. The lowest values of the pressure measures were in the midfoot, where the external part was more active than the internal part. Corresponding results have been reported using a computerized insole sensor [15]. In the present study, footprint analysis showed very symmetrical patterns between the right and the left legs with equal peaks and times of the sensor activation. From the slope and the duration of these footprint patterns a symmetry ratio can be calculated and used for searching gait abnormalities. The total footprint active area and peak pressure alone were less informative. The results from the non-parametric confidence intervals of all footprint parameters

Table 4
Canonical correlation between the subject characteristics (6), temporal gait (21), footprint $P*t$ (24), peak area (24), peak pressure (24) and peak time (24) sets of variables[a]

Set of variables	Canonical R	Chi- Square	p=
Subject characteristics versus $P*t$	0.882	219.3	0.00006
Subject characteristics versus peak pressure	0.845	198.5	0.001
Subject characteristics versus peak area	0.848	187.8	0.008
Subject characteristics versus peak time	0.865	185.8	0.01
Temporal gait variables versus peak time	0.983	672.94	0.00001
Temporal gait variables versus peak pressure	0.975	625.2	0.0002
Temporal gait variables versus $P*t$	0.957	620.4	0.0003
Temporal gait variables versus peak area	0.939	567.1	0.027

[a] In the brackets are the number of variables included in the set.

also support the idea that the variability in those trapezoids with concentrated observations are most informative and reliable and that data can be used in the assessment of gait motor control disturbances.

Plantar pressure distribution is related to walking speed so that with increasing velocity the vertical ground reaction forces increase at heel-strike and toe-off and decrease during mid-stance [2]. The increase in plantar pressures with increased cadence has been reported by Zhu et al. [21] using in-shoe pressure analysis. Our study revealed how the spatio-temporal variables, such as gait velocity and the duration of different phases of walking, were in concordance with the pressure sensor activations of the footprint. The footprint parameters were independent of age, however, heavier subjects had longer footprint peak time, larger active area in the midfoot and produced a higher peak pressure in the hindfoot.

As the GAITRite® system provides the FAP scores, we attempted to understand the value of this parameter for normal walking. It has been suggested that FAP is a quantitative representation of a person's gait and a reliable instrument in assessing different populations [13]. So far, its impact in the clinical diagnosis of minimal, mild and severe gait disorders is uncertain. In the present report, healthy men and women had lower mean FAP scores (56–100) than reported by Nelson et al. [13] even though they certainly had a symmetrical pattern of walking; their FAP scores unexpectedly decreased with increasing preferred velocity and cadence and decreasing the footprint peak time activation. The FAP calculation uses predetermined ranges of certain parameters for gait "normality" (normalized velocity, SL/LL ratio, step time, base of support, degree of left/right asymmetry and the use of orthotic devices) and it seems that the design of FAP calculation limits its use, especially with higher walking speeds. In a recent report [19], hemiparetic patients walked slower than normal subjects and when patients increased their walking velocity it increased their FAP scores, as expected. The FAP is a quick, robust measure only in rather unhurried gait and cannot substitute a more detailed, and therefore time-consuming, gait analysis. Fast, healthy gait, reaching velocities above 140 cm/s, is not well described by a FAP score and thus, beyond a predetermined gait velocity range, FAP deviations are expected in healthy subjects.

The results of the present study are in agreement with the geometrical concept of human gait where the step length is approximately the base of a triangle formed by two legs during a heel strike [12,20]. Using footprint analysis we showed the strict symmetry of normal gait and the close relationship between the footprint parameters, gait speed, body dimensions and spatio-temporal variables of gait. Other recording methods have found similar relationships between body dimensions, gait speed and spatio-temporal variables of gait [16]. Our findings were confirmed by the canonical correlation showing a significant relationship between the footprint variables and body dimensions and temporal gait parameters. Age of the subjects had no role with the exception of the base of support, where effect of age has also been reported by Grabiner et al. [7]. As shown by previous studies, age-associated changes in gait may be anticipated in a definitely older population than ours [3,16,17]. The pressure sensor system was easy to use, suitable for repetitive measurements and gave quickly information for both the temporal variables of gait and the footprint parameters.

In conclusion, the footprint patterns revealed the timing and high-degree of symmetry in the phases of normal walking and they also revealed the velocity performance. Therefore, footprint analysis and, in particular the forefoot peak pressure, may help in the clinical assessment of rehabilitation strategies, especially where evaluation of the plantar pressure distribution is valuable.

Acknowledgements

Neither an author nor any author's institution has received any commercial financial support related to this study. The GAITRite® equipment was purchased from the Finnish distributor with a regular price. The authors thank Mr. Paavo Könönen, MSc, and Mrs. Aila Keinänen, RN, for their help during the collection of the data. The Academy of Finland and Bulgarian Academy of Science and the Brain Research and Rehabilitation Center Neuron, Kuopio, Finland provided financial support for this work.

References

[1] D.G. Amstrong, E.J.G. Petters, K.A. Athanasiou, L.A. Lavery, Is there a clinical level of plantar foot pressure to identify patients with risk for neuropathic foot ulceration?, J Foot Ancle Surg 37 (1998) 303–307.

[2] T.P. Andriacchi, J.A. Ogle, J.O. Galante, Walking speed as a basis for normal and abnormal gait measurements, J Biomech 10 (1977) 261–268.

[3] R.W. Bohannon, Comfortable and maximum walking speed of adults aged 29-79: reference values and determinants, Age and Aging 26 (1997) 15–19.

[4] R.G. Cutlip, C. Mancinelli, F. Huber, J. Di Pasquale, Evaluation of an instrumented walkway for measurement of the kinematic parameters of gait, Gait Posture 12 (2000) 134–138.

[5] F.R. Finley, K.A. Cody, Locomotive characteristics of urban pedestrian, Arch Phys Med Rehabil 51 (1970) 423–426.

[6] GAITRite portable gait analysis system. GAITRite Operating manual 2001. SMS technologies Ltd, Elizabeth way, Harlow, Essex, CM19 5TL, UK.

[7] P.C. Grabiner, S.T. Biswas, M.D. Grabiner, Age-related changes in spatial and temporal gait variables, Arch Phys Med Rehabil 82 (2001) 31–35.

[8] H.R. Gretz, L.L. Doering, J. Quinn, M.E. Levin, Functional ambulation performance testing of adults with Down syndrome, NeuroRehab 11 (1999) 211–225.

[9] K.G. Holt, J. Hamill, R.O. Andres, Predicting the minimal energy cost of human walking, Med Sci Sport Exerc 23 (1991) 491–498.

[10] O.Y. Know, M.J. Mueller, Walking patterns used to reduce forefoot plantar pressure in people with diabetic neuropathies, Phys Ther 81 (2001) 828–835.

[11] A.L. McDonough, M. Batavia, F.C. Chen, S. Kwon, J. Ziai, The validity and the reliability of the GAITRite systeḿs measurements: a preliminary evaluation, Arch Phys Med Rehabil 82 (2001) 419–425.

[12] T.A. McMahon, Size and shape in biology, Science 179 (1973) 1201–1204.

[13] A.J. Nelson, L.J. Certo, L. Lembo, M. Nelson, The functional ambulation performance of elderly fallers and non-fallers walking at their preferred velocity, NeuroRehab 3 (1999) 141–146.

[14] J. Nilson, A. Thorstersson, Adaptability in frequency and amplitude of leg movements during human locomotion at different speeds, Acta Physiol Scand 129 (1987) 107–114.

[15] A.L. Randolph, M. Nelson, S. Akkapeddi, A. Levin, R. Alexandrescu, Reliability of measurements of pressure applied on the foot during walking by computerized insole sensor system, Arch Phys Med Rehabil 81 (2000) 573–578.

[16] R. Richard, J. Weber, O. Mejjad, D. Polin, F. Dujardin, P. Pasquin, X. Leloet, Spatiotemporal gait parameters measured using the Bessou gait analyzer in 79 healthy subjects. Influence of age, stature, and gender (Groupe de Recherche sur le Handicap de l'Appareil Locomoteur, GRHAL), Rev Rhum Engl Ed 62 (1995) 105–114.

[17] M.M. Samson, A. Crowe, P.L. de Vreede, J.A. Dessens, S.A. Duursma, H.J. Verhaar, Differences in gait parameters at a preferred walking speed in healthy subjects due to age, height and body weight, Aging 13 (2001) 16–21.

[18] StatSoft, Inc. STATISTICA for Windows. Tulsa, StatSoft, Inc., 2300 East 14th Street, Tulsa, OK 74104, 2000.

[19] E.B. Titianova, K. Pitkänen, A. Pääkkönen, J. Sivenius, I.M. Tarkka, Gait characteristics and functional ambulation profile in patients with chronic unilateral stroke. Am J Phys Med Rehab (in press) 2003

[20] V.M. Zatsiorsky, S.L. Werner, M.A. Kaimin, Basic kinematics of walking. Step length and step frequency. A review, J of Sport Med and Phys Fitness 34 (1994) 109–134.

[21] H. Zhu, G.F. Harris, J.J. Wertsch, The effect of walking cadence on plantar pressure, Arch Phys Med Rehabil 72 (1995) 1000–1005.

[22] H. Zhu, J.J. Wertsch, G.F. Harris, J.D. Loftsgaarden, M.B. Price, Foot pressure distribution during walking and shuffling, Arch Phys Med Rehabil 72 (1991) 390–397.

Ekaterina B. Titianova was born on 8th October 1958 in Bulgaria. She obtained her MD from the Medical Academy, High Institute of Medicine in Sofia, Bulgaria; and in 1987; an Acknowledged Speciality "Nervous Diseases", Ministry of Health, Medical Academy, Sofia, Bulgaria ; in 1990 a Ph.D. degree Doctor of Philosophy, People's Republic of Bulgaria, Council of Ministers, High Testimonial Board, Sofia, Bulgaria. From 2000 to date, she has been the Head of the Department of Neurology of the Second Clinic of Neurology, Specialized Hospital for Active Treatment of Neurology and Psychiatry, "St. Naum", Sofia, Bulgaria.

Plamen S. Mateev was born on 19th July 1948 in Sofia, Bulgaria. He obtained his PhD in Probability and Statistics from Lomonosov University, Moscow, Russia in 1978. Since 1996, he has been Head of Section Telecommunications at the Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, Bulgaria.

Ina M. Tarkka was born on 28th February 1956 in Tampere, Finland. She obtained her PhD at the University of Jyvaskyla, Jyvaskyla, Finland. Since 1996 she has been Director of Research, Brain Research and Rehabilitation Center Neuron, Kuopio, Finland. From 1992-1996, she was also the Assistant Professor, at Division of Restorative Neurology and Human Neurobiology, Baylor College of Medicine, Houston, Texas, USA.