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Original paper

Comparison of sensitivity coefficients for joint angle trajectory between normal and pathological gait

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Gait recordings exhibit intra-subject, inter-subject, within-trial and between-trial variability as well as data analysis methods. In medicine, comparison of different measuring method results or quantifying changes due to specific treatment is required. The aim of this study was to compare a group homogeneity with respect to dispersion around the reference curve and to compare waveforms of normal and pathological gait data based on joint angle curves. Data files were tracked using APAS system. Our own model of lower limb was used to calculate the trajectories of joint angles for 5 groups: healthy men, women, children, persons with drop foot and Trendelenburg's sign. Waveform parameterizations, *RMS*, *IAE* and correlation coefficients were used to compare joint angles with reference curve.

The sample scores obtained in this work provide an important information about closeness in the shape of two curves. Using multiple techniques of data analysis will benefit and give more accurate information.

Key words: *gait analysis, joint angle, root mean square, integral absolute error, correlation*

1. Introduction

In recent years, several approaches to gait data analysis have been studied, including such a complicate analysis as fuzzy systems, fractal dynamics and neutral networks. This type of study enables gait classification based on data which describe the same variable, e.g., normal and pathological gait, but it does not give any information about the range of differences in data sets. The analysis of quantitative gait data has traditionally been a difficult problem, because most of data are in time-series or curve form. To verify differences due to particular factors such as age or movement velocity and to quantify changes due to specific treatments such as botulinum injections or due to tendon lengths, we need to assess the similarities and differences between gait waveforms. Facing these challenges, summary statistics, e.g., mean, variance and waveform parameterizations (peaks amplitude), often provides restricted information about comparison of waveforms [1]. As we all know, there are no effective techniques for reducing gait data [2] and extracting useful information from waveform gait variables. Consequently, researchers have sill new ways to manipulate and interpret gait data, but they still search for the methods which might be useful for a particular aspect of gait data analysis. The purpose of the present work was to compare the properties and results of some methods based on the curves representing joint angles during gait with the goal of achieving a recommendation for standardized practice in comparing waveforms. It is found that statistical methods of data analysis are most widely applied and understood [3]. In order to compare the homogeneity of groups in terms of dispersion around the normative and reference curve and to compare the waveforms

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of normal and pathological gait data based on joint angle curves, three methods, i.e. waveform parameterization, correlation coefficients, *RMS* and *IAE* analyses, were used.

2. Material and methods

2.1. Characteristic of patients

The investigations were carried out in years 2007–2010 in the clinic (The Jerzy Popiełuszko Hospital in the Bielany District in Warsaw and Bródnowski Hospital in Warsaw) to establish the diagnosis in the case of disabled patients, and in the Main Laboratory of University of Physical Education in Warsaw in order to measure kinematic and kinetic data. The experiment was approved by the Ethics Senate Committee at the University of Physical Education in Warsaw. Before investigations patients were informed about their aim, the way and possibility of the resignation from participation and they gave informed consent before investigations. In the case of children, parents were present all the time during experiment, and they signed the agreement. The patients were divided into two groups: healthy and disabled persons, whose general characteristics is in table 1.

Ten healthy men (ZM, $n = 10$) and ten healthy women (ZK, $n = 10$) were chosen as a control group (ZMK). Persons with recognized paralysis or distability of lower limb muscles, i.e., drop foot, Trendelenburg–Duchenne sign, were classified into the second group. OS group was characterized by: discopathy at L_4/L_5 or/and L_5/S_1 levels, significant weakness of ankle extensors, especially of m. tibialis anterior, peroneal muscular atrophy or weakness and numbness of foot. OTD group was characterized by: hip degeneration, weakness of hip abductors, i.e., gluteus medius and minimus. All patients from this group needed hip arthroplasty.

2.2. Method of acquisition kinematic and kinetic data

Gait analysis was carried out using the APAS system with one video camera, PENTAX Tv Zoom, Lens 8–48 mm, for the acquisition of kinematic variables. The camera recorded sagittal plane of volunteers motion (figure 1). One Kistler platform was used to measure ground reaction forces. Kinematic and kinetic data were digitized at a sampling rate of 50 Hz. A cubic (1 m × 1 m × 1 m) metal box was used for the calibration procedure and made up the laboratory frame reference.

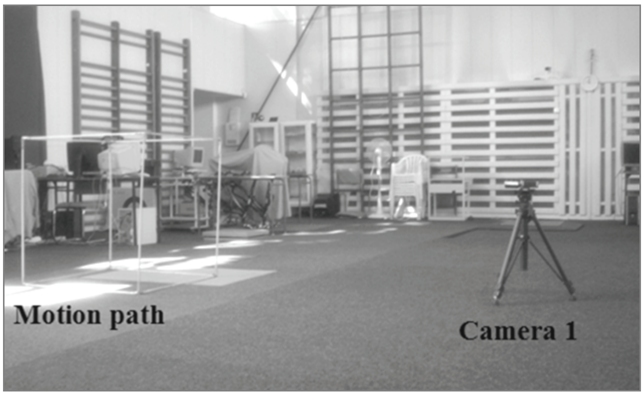

Fig. 1. Measuring setup for motion analysis

Kinematic data were collected from 5 passive markers. The positions of markers are shown in figure 2. Such location of markers allowed construction of biomechanical model of lower limb composed of four rigid bodies: foot, shank, thigh and trunk.

Table 1. Minimum, maximum, means and standard deviations for morphological data of participants

Group		Healthy persons' groups			Disabled persons' groups	
		ZM group ($n = 10$)	ZK group ($n = 10$)	ZD group ($n = 10$)	OS group ($n = 10$)	OTD group ($n = 10$)
Group profile		Healthy men	Healthy women	Healthy children	Patients with drop foot	Patients with Trendelenburg–Duchenne sign
Age	$\bar{x} \pm SD$	23.6 ± 2.1	28.4 ± 7.3	5.7±0.6	56.5 ± 16.5	63.2 ± 12.2
	min–max	22–29	21–38	5–6.5	31–75	47–79
Body mass (kg)	$\bar{x} \pm SD$	74.5 ± 7.2	62 ± 6.9	22.1±4.6	73.1 ± 20.0	75.1 ± 10.9
	min–max	65–85	53–75	15.2–30	51–115	62–92
Body height (cm)	$\bar{x} \pm SD$	176.8 ± 7.2	167.6 ± 6.3	118.9±7.4	164.8 ± 6.3	167.8 ± 9.6
	min–max	168–188	154–178	108–130	158–177	158–184

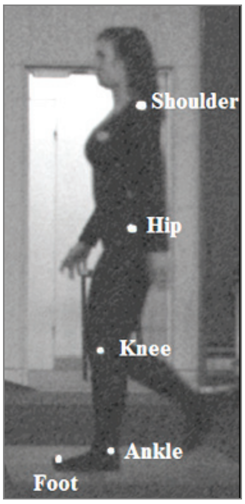

Fig. 2. Marker attachment locations during experiment

Each subject was instructed to walk at self-selected speed along a level surface of approximately 10 m in length. Each subject took part in one valid trial. A valid trial was defined as that in which subjects struck the force platform without adjusting their stride length. A stride was considered as the time between two consecutive heel–floor contacts of the same limb [4].

2.3. Mathematical model of lower limb

In order to eliminate errors resulting from different limb lengths in each frame and to increase the accuracy of joint angle data, the free body diagram of lower limb was used (figure 3). Sagittal plane angles were calculated using markers' trajectories during walking. Applying two-argument variant of arctangent $a\tan2(X, Y)$, segments' deviation from vertical line θ_i and the angles between segments Φ_i were computed:

$$\theta_i = a\tan 2(X_i - X_{i+1}, Y_i - Y_{i+1}) \quad \text{for} \quad i = 1, 2, 3, 4,$$

$$\Phi_i = \pi - \theta_{i+1} + \theta_i \quad \text{for} \quad i = 1, 2, 3,$$

where:

X_i, Y_i – the i-th segment marker coordinates,

θ_i – the i-th segment deviation from vertical line,

Φ_i – the i-th joint angle of lower limb.

All data were reduced to 100 samples over the gait cycle and smoothed using *Spline Toolbox* from MatLab collection.

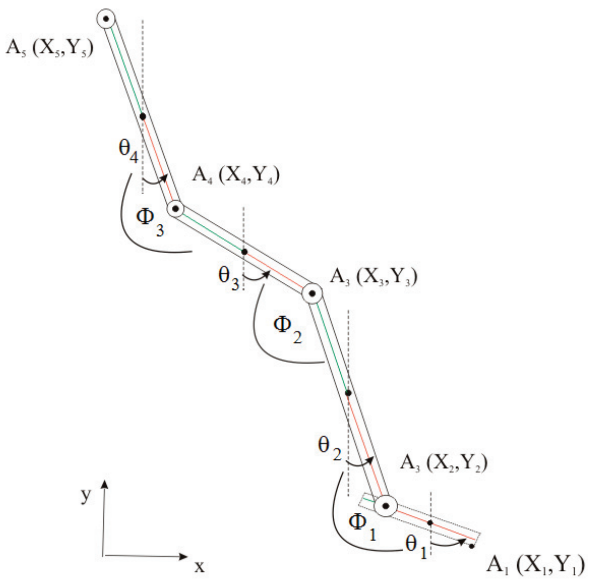

Fig. 3. Free body diagram of lower limb:
Φ_1 – ankle angle, Φ_2 – knee angle, Φ_3 – hip angle

2.4. Methods of data analysis

Three methods: waveform parameterization, the analysis of correlation coefficients, *RMS* and *IAE* coefficients were used in order to compare the reference curve with the trajectories of joint angles calculated in gait cycle domain for five groups: healthy men (ZM), healthy women (ZK), healthy children (ZD), persons with drop foot (OS) and persons with Trendeleburg–Duchenne sign (OTD). Reference curve was defined as an average trajectory calculated for each joint for ZM and ZK groups together.

Waveform parameterization. For each curve representing the groups examined, peak flexion and extension were computed. The t-test was used to find significant differences in peaks on reference curve and in joint angles' trajectories computed for each group.

Analysis of correlation coefficients. In order to compare the closeness of the two curves in the shape, the correlation coefficients were used. In this case, the average trajectories for each group were compared with reference trajectory (ZMK). The correlation between the i-th variable of average trajectory in given a group (ZM, ZK, ZD OS or OTD) and the j-th variable in group ZMK was computed for every joint using MatLab function given by formula: corrcoef(X, ZMK). The general formula to compute correlation coefficient for two signals X and Y is as follows:

$$r = \frac{N\Sigma XY - (\Sigma X)(\Sigma Y)}{\sqrt{[N\Sigma X^2 - (\Sigma X)^2][N\Sigma Y^2 - (\Sigma Y)^2]}},$$

where N is the sample number.

Analysis of RMS and IAE coefficients. In order to compare the trajectories of joint angles and the homogeneity of groups in terms of dispersion around normative and reference curve, the following methods were used: Root Mean Square Error (RMS), Integral Absolute Error (IAE), Shapiro–Wilk test and Student's *t*-test. *RMS* and *IAE* coefficients are given by the following formulas:

$$RMS = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}(\varphi_{\text{ZMK}} - \varphi_i)^2}{\frac{1}{N}\sum_{i=1}^{N}(\varphi_{\text{ZMK}})^2}},$$

$$IAE = \frac{1}{100}\left|\int_a^b |\varphi_i| - \int_a^b |\varphi_{\text{ZMK}}|\right|,$$

where:

$i = 1, 2, 3, \ldots, 10$ – the number of individuals in a given group,

N – sample size,

φ_i – the trajectories of joint angles for *i*-th subject,

φ_{ZMK} – average and normative curve for each joint in the control group,

a, b – the boundaries of the integration interval $[a, b]$, where $a = 0$, $b = 100$.

The coefficients *RMS* and *IAE* were calculated for each person assigned to one of the given groups. Every group was characterized by ten such variables. Using the Shapiro–Wilk test the normality of *RMS* and *IAE* distributions was checked. The homogeneity of groups in terms of dispersion around the reference curve was compared for each lower limb joint. Depending on the result, *t*-test was applied to normal distribution or the Mann–Whitney *U* test for others.

3. Results

3.1. Kinematic data and waveform parameterizations

The sagittal ankle, knee, and hip data are shown in figures 4 and 5. For ankle motion (figure 4) without any detailed statistical analysis, it is readily ob-

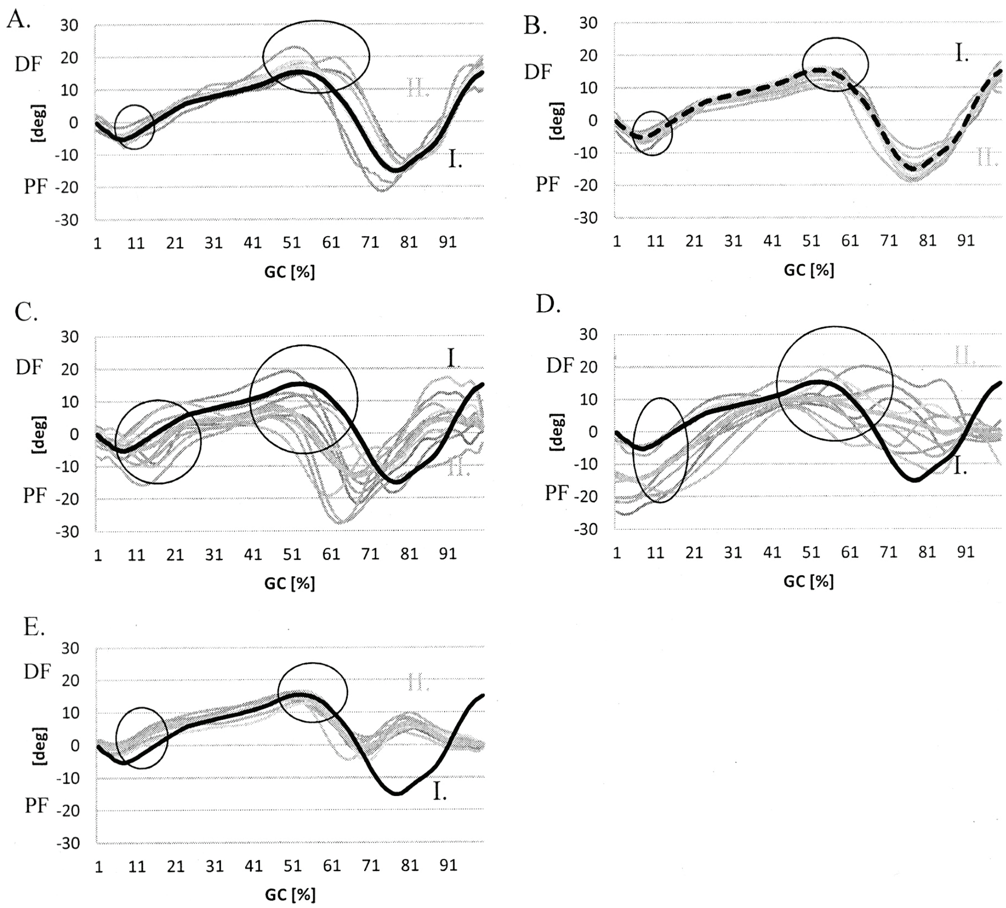

Fig. 4. Ankle plantarflexion (PF) and dorsiflexion (DF) for:
A. – healthy men (ZM), B. – healthy women (ZK), C. – healthy children (ZD), D. – drop foot (OS), E. – Trendelenburg–Duchenne (OTD). I. – average trajectory in control group, II. – average trajectory computed in each group

servable that average trajectories in ZM and ZK groups have the same shape as that in the reference group ZMK (healthy men and women together). While the average joint angle curves obtained in each OS and OTD groups have different shapes and trajectory dispersions compared to the reference group. The same results were obtained for the knee and hip joint angles. In ankle motion during normal gait, maximal value of plantarflexion is observed during the first 0–12% of GC; however, the maximal value of dorsiflexion occurs at the interval of 12–62% of GC during midstance and the first half of terminal stance. For ankle motion, only the values for these intervals were taken under consideration in waveform parameterizations.

To see the differences between the groups, mean plantarflexion and dorsiflexion peaks during gait cycle for every group are shown in table 2. In order to find statistically significant differences between reference group and others, *t*-test was used. In the case of ZMK, statistically significant differences ($p < 0.05$) were observed in plantarflexion peak achieved in OS (more than 174% in ZMK) and in OTD (less than 88% in ZMK). Significant difference was found in dorsiflexion peak in ZD (less than 50% in ZMK).

The same method allowed knee and hip angles to be analysed. In order to point flexion and extension peaks at those angles only the trajectories for healthy men are shown in figure 5. Two peaks of knee flexion were taken under consideration in waveform parameterizations. The first flexion peak occurred at 0–50% of GC and the second maximal peak were observed at 60–100% of GC in all cases (figure 5A).

In comparison with the reference group, statistically significant differences were observed for both values in OS and OTD (table 3). In both cases, the average values were significantly lower than the reference.

Sagittal plane of hip motion is presented in figure 5B. Two peaks of hip motion in flexion and ex-

Table 2. Mean plantarflexion and dorsiflexion peaks during ankle motion for each group, significance at $p < 0.05$ level (*) in Student's *t*-test

	ZMK	ZM	ZK	ZD	OS	OTD
Mean peak of plantarflexion	–5.31°	–4.99°	–5.67°	–4.61°	–14.59° *	–0.92° *
Mean peak of dorsiflexion	15.38°	16.75°	14.04°	7.62° *	10.20°	14.58°

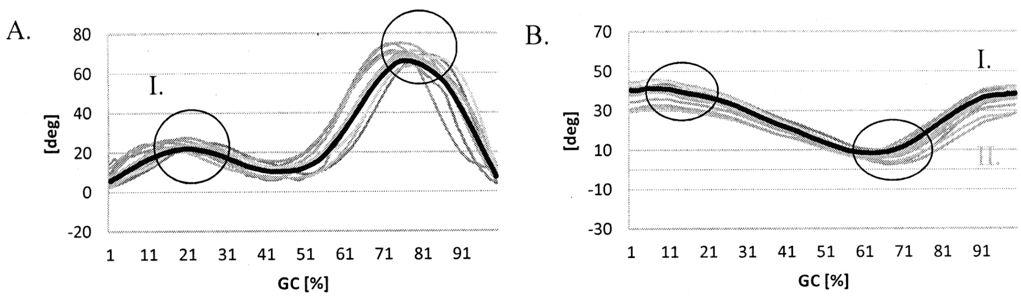

Fig. 5. A. – knee flexion–extension, B. – hip flexion–extension in healthy men (ZM) group. I. – average trajectory in control group, II. – average trajectory computed in every group

Table 3. Means of the first and second flexion peaks during knee motion for each group, significance at $p < 0.05$ level (*) in Student's *t*-test

	ZMK	ZM	ZK	ZD	OS	OTD
First maximal peak	22.03°	23.06°	21.09°	19.31°	14.10° *	14.18° *
Second maximal peak	66.26°	69.00°	63.51°	61.33°	20.60° *	43.07° *

Table 4. Mean flexion and extension peaks during hip motion for each group, significance at $p < 0.05$ level (*) in Student' *t*-test

	ZMK	ZM	ZK	ZD	OS	OTD
Flexion peak	41.29°	42.84°	39.94°	44.01°	32.87° *	23.33° *
Extension peak	8.50°	9.68°	7.00°	8.62°	2.46° *	–15.66° *

tension were taken under consideration in waveform parameterizations. The flexion peak occurred at 0–30% of GC in each group. The extension peak was observed at 40–90% of GC. As before, in comparison with the reference group, statistically significant differences were observed for both values in OS and OTD (table 4). In both cases, the average values were significantly lower less than the reference.

3.2. Comparison of curve shapes – correlation analysis

In order to compare the closeness of the two curves in the shape, the correlation coefficients were used. In this case, the average trajectories for every group were compared with the reference one for every joint. The results are shown in table 5.

For interpretation of the results presented in table 5, an appropriate agreement categorization was done (table 6). In relation to the strength of agreement presented in table 6, the results computed (table 5) can be described as follows: For any joint in ZM and ZK groups there were noted strong associations, as in the case of ZD for knee and OS for hip curves. Moderate associations in the case of ankle joint in ZD and OTD, knee joint in OTD and hip in ZD, OTD groups were observed. Weak association was noted in the case of ankle joint in OS, and for knee joint in the same group there was no relationship.

Table 5. Correlation coefficients computed for relation of average trajectories in each group to reference

	Ankle	Knee	Hip
ZM vs. ZMK	0.9994	0.9992	0.9966
ZK vs. ZMK	0.9993	0.9991	0.9964
ZD vs. ZMK	0.5776	0.9507	0.7818
OS vs. ZMK	0.4760	0.0020	0.9116
OTD vs. ZMK	0.5830	0.8858	0.8674

Table 6. Agreement categorization for correlation coefficient value

Correlation coefficient intervals	Strength of agreement
1	Perfect relationship
[0.9; 1)	Strong association
[0.5; 0.9)	Moderate association
[0.2; 0.5)	Weak association
[0; 0.2)	No relationship

3.3. Analysis of group homogeneity – *RMS* and *IAE* analyses

In order to compare joint angle trajectories and group homogeneity with respect to dispersion around

Table 7. *p*-values and statistically significant differences (*$p < 0.05$) in *RMS* and *IAE* for joint angles in Student's *t*-test

	Ankle		Knee		Hip	
	RMS	*IAE*	*RMS*	*IAE*	*RMS*	*IAE*
ZM vs. ZK	0.23	0.58	0.17	0.76	0.83	0.80
ZM vs. ZD	0.00*	0.00*	**0.02***	**0.69**	**0.00***	**0.60**
ZM vs. OS	**0.00***	**0.76**	0.00*	0.00*	0.00*	0.02*
ZM vs. OTD	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
ZK vs. ZD	0.00*	0.01*	**0.02***	**0.96**	**0.00***	**0.84**
ZK vs. OS	**0.00***	**0.77**	0.00*	0.00*	0.00*	0.05*
ZK vs. OTD	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
ZD vs. OS	**0.54**	**0.00***	0.00*	0.00*	**0.93**	**0.03***
ZD vs. OTD	0.16	0.89	0.00*	0.00*	0.00*	0.00*
OS vs. OTD	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*

Table 8. Intervals of *IAE* and *RMS* values and strength of agreement

Interval	*IAE* interval	*RMS* interval	Strength of agreement
$[0, \bar{x} - 2SD)$	[0; 4.71)	[0; 0.36)	Strong association
$[\bar{x} - 2SD, \bar{x} - SD)$	[4.71; 4.99)	[0.36; 0.42)	Substantial
$[\bar{x} - SD, \bar{x})$	[4.99; 5.27)	[0.42; 0.48)	Moderate association
$[\bar{x}, \bar{x} + SD)$	[5.27; 5.55)	[0.48; 0.54)	Weak association
$[\bar{x} + SD, \bar{x} + 2SD)$	[5.55; 5.83)	[0.54; 0.60)	Poor
$[\bar{x} + 2SD, \bar{x} + 3SD)$	[5.83; 6.11)	[0.60; 0.65)	No relationship

the reference curve, root mean square error (*RMS*) and integral absolute error (*IAE*) methods were used. The coefficients *RMS* and *IAE* were calculated for each person assigned to one of the given group. Each group was characterized by ten such variables. Groups' homogeneity with respect to dispersion around reference curve was compared for each lower limb joint. In table 7, *p*-values for the coefficients *RMS* and *IAE* are presented. The valuation of both coefficients is consistent in 74%. While the differences between *RMS* and *IAE* were observed in the following relations: ZM vs. ZD, ZK vs. ZD for knee and hip joints, ZD vs. OS only for hip joint and ZM vs. OS, ZK vs. OS, ZD vs. OS for ankle. In these cases, except ZD vs. OS for ankle and hip joint, the statically differences were noted for *RMS* coefficient.

In order to describe the strength of agreement between reference curve and others, the appropriate intervals for *RMS* and *IAE* coefficients were counted (table 8). To calculate the classification intervals only *RMS* and *IAE* coefficients were used for healthy men and women groups.

3.4. Comparison of methods

Comparison of the methods presented in this paper is shown in table 9. For waveform parameterizations *p*-value in *t*-test was used to describe the significant differences in peaks between reference curve and joint trajectories computed for each person in each group. In the case of correlation coefficients, the agreement categorization (table 6) was taken for the results presented in table 5. The *RMS* and *IAE* methods presented in this paper shows groups' homogeneity with respect to dispersion around the reference curve. The results of this analysis were described earlier. However, in table 9 for *RMS* and *IAE* coefficients there is presented only the valuation from interval (table 8), where the largest number of persons fell. The values of *RMS* and *IAE* were computed for every joint for each person in comparison with the reference curve.

The results presented in table 9 show full agreement between four methods for groups ZM and ZK in comparison to reference curve (ZMK) for ankle, knee and hip angle trajectories. The agreement was defined as a strong association. A moderate association (correlation), no relationship (*RMS*), a strong association (*IAE*), and a significant difference only for dorsiflexion were noted in the case of ZD group for ankle joint in comparison to the reference curve. However, for knee angle a full agreement (strong association) was reached and for hip only for *RMS* and *IAE* a strong association was noted. A moderate association was found between the correlation coefficients of hip, and in parameterization analysis significant differences in knee and hip angles

Table 9. Strength of agreement and comparison of methods

	Group	Waves parameterization *p*-value in *t*-test		Correlation	*RMS*	*IAE*
Ankle		Min	Max			
	ZM	0.64	0.12	strong association	strong association	strong association
	ZK	0.64	0.96	strong association	strong association	strong association
	ZD	0.15	0.00*	moderate association	no relationship	strong association
	OS	0.00*	0.10	weak association	no relationship	strong association
	OTD	0.00*	0.14	moderate association	no relationship	strong association
Knee		Max 1	Max 2			
	ZM	0.06	0.06	strong association	strong association	strong association
	ZK	0.17	0.28	strong association	strong association	strong association
	ZD	0.92	0.07	strong association	strong association	strong association
	OS	0.00*	0.00*	no relationship	no relationship	no relationship
	OTD	0.00*	0.00*	moderate association	weak association/ poor	no relationship
Hip		Max	Min			
	ZM	0.10	0.99	strong association	strong association	strong association
	ZK	0.19	0.98	strong association	strong association	strong association
	ZD	0.06	0.42	moderate association	strong association	strong association
	OS	0.00*	0.00*	strong association	strong association	no relationship
	OTD	0.00*	0.00*	moderate association	no relationship	no relationship

were observed. In OS and OTD groups, for each joint the significant differences in each peak were noticed in comparison to the references curves. In OS group, no relationship was found for knee angles for: correlation, *RMS* and *IAE*. In OS, for hip there existed a strong association (correlation and *RMS*) and no relationship (*IAE*) in comparison with reference curve. Based on the analysis of the results obtained for OTD group in comparison to reference, the moderate association (correlation), no relationship (*RMS*) and strong association (*IAE*) were noted for ankle joint. The differences between curves, respectively, moderate association – correlation, weak/poor – *RMS* and no relationship – *IAE* were noted for knee. In the case of hip in OTD group, no relationship (*RMS*, *IAE*) and a moderate association (correlation) were observed.

4. Discussion

The methods applied in this work, i.e., waveform parameterization, correlation coefficients, the analysis of *RMS* and *IAE* coefficients, and the results presented for joint angle analysis were shown in order to find a good and accurate way of comparing the group homogeneity with respect to dispersion around the normative and reference curve and in order to compare the waveforms observed for normal and pathological gait data. The analysis of quantitative gait data has traditionally presented a serious scientific challenge. In paper [3], the potential of various methods as fuzzy and fractal analyses of gait data is reviewed, but it has been found that statistical methods are most widely applied and understood. The waveform parameterization presented in this paper proved to be the simplest and commonly used method both in description and in comparison of normal and pathological gait. GANLEY and POWERS [5] used peak amplitude analyzing: joint angles, moments, and power trajectories obtained during adults and 7-year-old children walking. The results received in 7-year-olds group were similar to those of adults. However, children demonstrated a diminished peak of plantarflexor moment and the generation of less power absorption peak in the ankle during late stance. These results support the hypothesis that children lack the neuromuscular maturity, especially in the ankle, thus they cannot produce an adult gait pattern, but there is no description of the shape differences between analysis curves. Similar analysis was carried out by GAUDREAULT et al. [6], who used a descriptive statistics to characterize the groups. Student's *t*-test was chosen to examine the significance of the differences observed in groups between: time–distance variables and peak values estimated during stance phase and swing phases – joint angles data; during loading and terminal stance – joint moments and power data. The level of significance was set at $p < 0.05$. These ways of analysis are commonly used and also in the present paper they allow us to show that joint angle curves in OS and OTD groups are significantly different from reference, but only for characteristic peaks, selected in waveform parameterizations.

The second method presented in this paper was based on correlation coefficients which allowed comparison of the closeness of the two curves in the shape and their agreement categorization (table 6). Similar interpretation was found in [7]. More sophisticated analysis is presented in order to compare the homogeneity of groups with respect to dispersion around the normative and reference curve. Root mean square error (*RMS*) and our own coefficient of integral absolute error (*IAE*) were used. *RMS* is one of two ways to quantify the difference between values. NENE et al. [8] show the validity of the model of lower limb computed on the basis of the root mean square differences between the integrated gyroscope signals and the reference angles. MAYAGOITIA et al. [9] propose the root of the mean of the square differences for comparison between the accelerometer sensor and Vicons results, and they compare the closeness in amplitude. But in any of various methods presented, the connection between *RMS* and *IAE* was not found. The results presented in this paper demonstrate the variability and data dispersion around normative curve in the whole domain of analysis. The valuation of both coefficients was consistent in 74%. The interval and agreement categorization shown in table 8 can help clinicians to see the range of differences between curves and to describe the differences in the whole domain. The results obtained show significant differences in homogeneity of groups with respect to dispersion around the normative and reference curve.

5. Conclusion

The pattern recognition techniques presented are promising tools for clinical gait analysis, especially *RMS* and *IAE* gait data analysis which permits analysis of the homogeneity of groups with respect to dispersion around the reference curve. The scores obtained provide important information about the closeness of the two curves in the shape. However, correlation coefficients seem to be good additional method in comparison with the closeness of the two curves in the shape.

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