J Musculoskelet Neuronal Interact 2013; 13(2):244-250

Original Article

Hylonome

Kinematic quantification of gait asymmetry in patients with peroneal nerve palsy based on bilateral cyclograms

P. Kutilek[1], S. Viteckova[1], Z. Svoboda[2], P. Smrcka[1]

[1]Faculty of Biomedical Engineering, Czech Technical University in Prague, nam. Sitna 3105, 272 01 Kladno, the Czech Republic;
[2]Faculty of Physical Culture, Palacky University of Olomouc, Tr. Miru 115, 771 11 Olomouc, the Czech Republic

Abstract

Nowadays, bipedal walking is undergoing extensive study. Several methods can be used in physiotherapeutic research for identifying defects in bipedal walking as a result of pathology of the musculoskeletal or nervous system. Our work focuses on studying asymmetry of walking based on synchronized bilateral knee-knee cyclograms. Participants presenting with peroneal nerve palsy and foot drop were included in the study. The bilateral cyclograms, also called angle-angle diagrams, were created to quantify gait asymmetry before and immediately after application of a brace. In order to quantify the asymmetry of human walking, we have described and tested the application of the method based on the inclination angle of the synchronized bilateral cyclograms. The symmetry index (SI) was used as a comparative method to evaluate the symmetry of bipedal walking. The method based on the orientation of the cyclograms can be used as an additional method for determining the gait asymmetry. The new technique has never been applied before to study the gait asymmetry in patients with peroneal nerve palsy or patients with leg brace.

Keywords: Human Ealking, Leg Brace, Foot Drop, Cyclogram, Peroneal Nerve Palsy

Introduction

Currently, several methods can be used in physiotherapeutic research for identifying defects in bipedal walking as a result of pathology of the musculoskeletal or nervous system. The most widely used technique for studying gait in clinical practice is gait phase analysis[1-3]. Very intensive research is now being done on using electromyography (EMG) measurements to study musculoskeletal system of lower limbs[4-6]. For a study of gait we used method based on an analysis of gait angles using cyclograms (also called angle-angle diagrams or cyclokinograms). The first mention of the cyclogram argued that a cyclic process such as walking is better understood when studied with a cyclic plot[7]. The creation of cyclograms is based on gait angles that are objective and well suited for statistical study[8-12].

The authors have no conflict of interest.

Corresponding author: Dr. Patrik Kutilek, Czech Technical University in Prague, Nam. Sitna 3105, 272 01 Kladno, Kladno, 272 01, Czech Republic
E-mail: kutilek@fbmi.cvut.cz

Edited by: F. Rauch
Accepted 26 February 2013

We focus on the potential use of cyclograms for the evaluation of the gait asymmetry in patients with peroneal nerve palsy and/or patients with leg brace. Symmetry is an important indicator of healthy gait or proper walking technique. Gait symmetry can be affected negatively by various factors. Several methods can be used for identifying asymmetry in bipedal walking. At present, algebraic indices and statistical parameters represent two major classes of symmetry quantifiers[13-16]. Algebraic indices include the symmetry index and the ratio index. Symmetry index and the ratio index compare bilateral variables such as maximum joint angles. These parameters depend on discrete variables and are unable to reflect the asymmetry as it evolves over a complete gait cycle. Statistical methods such as paired t-test and PCA, and parameters such as correlation coefficients, coefficient of variation and variance ratio have also been used to quantify the gait asymmetry[13,17]. These parameters do not usually suffer from the limitations of the algebraic indices, but their computation is more complex and interpretation is less clear. In 2003, Goswami introduced a technique based on the geometric properties of symmetric angle-angle diagrams[13], also called bilateral cyclograms[13]. The technique is rooted in geometry and the symmetry measures are intuitively understandable. The cyclograms are closed trajectories generated by simultaneously plotting two joint variables. In order to quantify the symmetry of bipedal walking, in the study was used a synchronized bilateral cyclogram which represents the same joint and two sides of the body[13], i.e. the approach is based on the symmetry of joint angle evolutions[13,18]. The area within the synchronized bilateral cyclogram and its orientation are parameters used to evaluate the symmetry[13,19,20]. For the absolutely symmetrical gait, the area within the curve is zero and its orientation is forty five degrees[13].

In our work, we will describe and test the application of method based on the cyclogram orientation (i.e. inclination) to analyze the gait of participants with peroneal nerve palsy[21] and leg brace. Peroneal nerve palsy is the most common entrapment mononeuropathy in the lower extremity. Patients usually present with a foot drop and sensory disturbance over the lateral calf and the dorsum of the foot. Foot drop is the common name for a condition called dorsi-flexion weakness of the foot[22]. To dorsiflex the foot while walking, orthopedic devices, i.e. orthoses, were developed. These devices may include braces, splints, figure-eight elastic straps, orthopedic shoes, and any other means. The orthoses are divided into three main categories: conventional ankle foot orthosis (AFOs), dynamic ankle foot orthoses (DAFOs) or carbon composite ankle foot orthoses (C-AFO)[23].

In the case of the use of orthosis for dorsiflexion, the ankle angle is directly affected by the brace. The hip angle is more difficult to measure accurately and is affected by the knee angle. On the other hand, the knee angle is commonly measured for purposes of orthopedics and rehabilitation applications[24]. For these reasons, we will test the application of method based on the cyclogram orientation (i.e. inclination) by using measured knee joint angles.

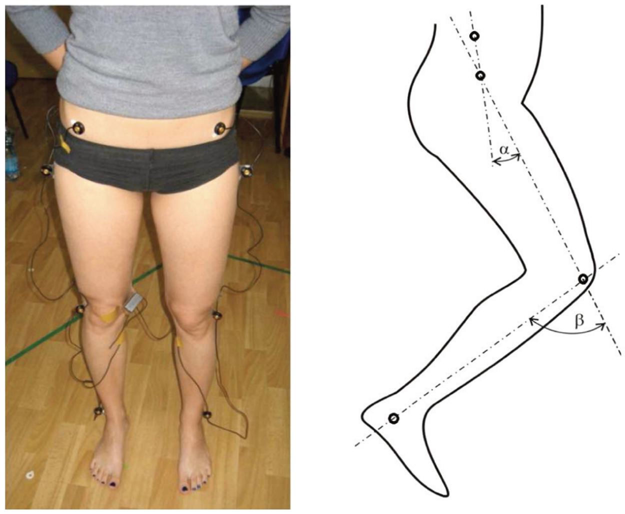

Figure 1. Example of the location of IR markers and angles measured during the examination[19].

Methods

Participants

The set of data to create and study angle-angle diagrams was measured on nine volunteers/adult participants (age of 46±15 years) with peroneal nerve palsy. They were recruited from patients of the Rehabilitation Center Kladruby (Kladruby u Vlasimi, the Czech Republic). Participants (four women and five men) were randomly selected, with different ages, weights and underlying diseases. All participants were characterized by the presence of a foot drop. Some of them had uncomplicated surgical interventions and the passive ankle stretching was implemented in the rehabilitation protocol. Participants were qualified for a one-week rehabilitation stay at clinic and selection of appropriate brace. All participants were measured at the beginning of the rehabilitation stay.

Measurement equipment

We can use several methods and MoCap systems for measuring movements in two/three dimensional space. We used medical camera system with active markers, Lukotronic AS 200 (Lutz Mechatronic Technology e.U.) system. Active LED markers were placed on the following anatomical points: malleolus lateralis, epicondylus lateralis, trochanter major and spina iliaca anterior superior, Figure 1. The markers are placed in accordance with the recommendation of the manufacturer of the widely-used Lukotronic AS 200 system with GaitLab software[25-27] (Lutz Mechatronic Technology e.U.). Infrared markers are fixed only on the lower parts of body, i.e. lower limbs. We also used GaitLab software and MatLab Simulink (The MathWorks Inc.) software to identify the joint angles of the lower limbs[19,28,29]. Kinematics model in the GaitLab software is used to identify the angles and MatLab Simulink[19,28] is used for graphical presentation and further processing in the MatLab software (i.e. creation of 2D diagrams, identification of the forefoot / foot flat-touchdown, etc.). Using these techniques, we can record and study the movement in a three-dimensional space, though we primarily study the movement in a two-dimensional sagittal plane.

Participants were asked to walk without an orthosis, and with Foot-Up splint and calf mounted support strap. The Foot-Up splint (made by Össur h.f. of Reykjavik, Iceland) is a lightweight non-plastic ankle orthosis, i.e. “DAFO”, designed to provide support for drop foot. This orthosis provides improvement in the patient’s gait by providing a support moment, i.e. the foot is raised. The Foot-Up splint combines two separate parts; an ergonomic ankle wrap/cuff, which connects to a plastic inlay (or strap) that fits between the tongue and the laces of a shoe. The calf mounted support strap, type 702(long), (made by SANOMED s.r.o. of Brno, Czech Rebublic) is a lightweight plantar fasciitis splint, i.e. “DAFO”. The vertical support strap combines two separate parts; an ergonomic calf wrap, which connects to a plastic inlay (or strap) that fits between the tongue and the laces of a shoe.

Test procedure

The participants were asked to walk properly on a treadmill. The walking speed was 2.3 km/h for studying the proposed method. We assume that improvement or deterioration of gait symmetry is not primarily influenced by walking speed. First, participants walked without the orthosis and any support devices, and the joint angles (left/right knee angles) were measured on participants. After that, the physician recommended appropriate orthopedic devices (Foot-Up splint and support strap) to dorsiflex the foot at the ankle. Then participants were asked to walk immediately after the application of two types of orthopedic devices. Nine participants were measured three times: without orthosis, with Foot-Up splint and with calf mounted support strap.

Data processing

After obtaining the measured data, we identified joint angles and created unsynchronized bilateral cyclograms in MatLab software[13,18], Figure 2. The deviations of the angles are also caused, for example, by a tremor of a body part or parts, Figure 2. Therefore, it is necessary to create a cyclogram by using unfiltered measured data about the joint angles, Figure 2.

After the measurement, data processing and calculation of knee joint angles[28,29], we used the method based on synchronization of two angle plots to obtain bilateral knee-knee cyclograms[13]. A prominent gait event such as the heel-touchdown or forefoot/foot flat-touchdown (in the case of patients with movement disorders) was used to synchronize the two plots. The vertical position, velocity and acceleration of the marker on the malleolus lateralis is also measured (by the Lukotronic AS 200) and plotted to identify (by the MatLab) the ground foot contact. Ground foot contact is determined by the first peak (corresponding to the impact i.e. significant deceleration of the whole foot) in the vertical velocity and acceleration curve of the marker on the malleolus lateralis within a window of the order of one gait cycle[30]. The identification was made by MatLab, and final verification was made by a person in order to ensure maximum accuracy of the synchronization. For accurate calculation of geometric characteristic of the cyclogram (i.e. inclination angle), only the measured data describing the entire cycles are used. The first and last 3 gait cycles of each walking trial were excluded from the analysis to avoid acceleration and deceleration phases and only cycles corresponding to a constant speed are used. We used three or four entire gait cycles of each walking trial to determine the value of the geometric characteristic of a cyclogram.

The two-dimensional synchronized bilateral cyclogram, Figure 2, represents a set of states of the two knee angles. For a symmetric gait a properly synchronized twin trajectories from corresponding joints should be identical, and synchronized bilateral cyclogram should lie on a symmetry line[13]. The "ideal" symmetry line is a straight line passing through the origin inclined at an angle 45°. We can mathematically calculate the cyclogram's deviation from the "ideal" symmetry line to obtain a quantification of gait symmetry. Therefore, we use the orientation of cyclogram to evaluate the symmetry[13].

The plotted bilateral cyclogram represents a set of states, and thus we can use the Linear regression to determine the value of inclination (i.e. cyclogram orientation). Linear regression is the least squares estimator of a linear regression model[29,31]. Simple linear regression fits a straight line (axis) through the set of points (i.e. states). The polynomial equation of the major axis regression (principal axis) is:

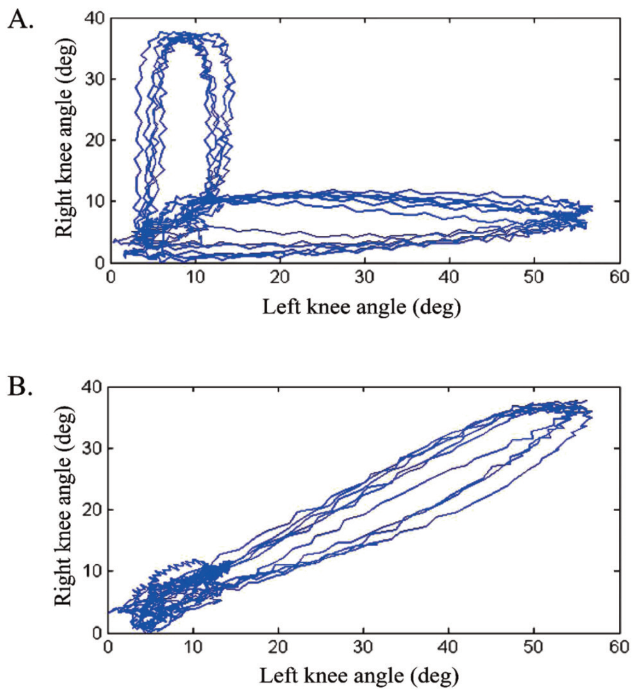

Figure 2. Example of an unsynchronized bilateral knee-knee cyclogram **(A)** and the synchronized bilateral cyclogram **(B)**.

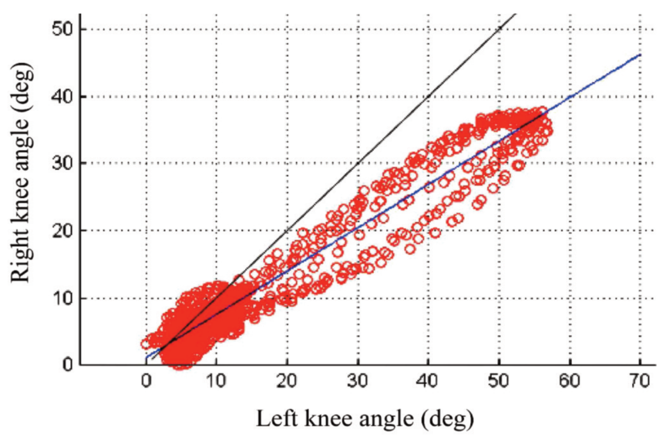

Figure 3. Example of a synchronized bilateral cyclogram with the principal axis and symmetry line.

$$\beta_R = \alpha_0 + \alpha_1 \cdot \beta_L, \quad (1)$$

α_0 and α_1 are parameters identified by estimator (i.e. MatLab software). When β_R is the dependent variable of the first angle, i.e. right knee angle, and the β_L is the independent variable of the second angle, i.e. left knee angle, the direction (slope) of

A. Measured data						
Participant	**Inclination angle (deg)**			**Symmetry index (-)**		
	Without orthosis	Foot-Up splint	Support strap	Without orthosis	Foot-Up splint	Support strap
1.	47.6	43.1	44.1	0.88	0.96	1.04
2.	22.4	43.2	49.5	0.64	0.71	0.68
3.	51.3	56.6	62.9	1.27	1.45	1.95
4.	57.5	52.9	21.7	0.53	0.73	0.56
5.	41.6	49.7	49.6	0.88	0.89	0.89
6.	40.6	38.1	34.9	0.80	0.84	0.89
7.	49.3	59.3	71.2	0.53	0.43	0.40
8.	48.0	45.0	40.5	1.01	1.03	1.15
9.	42.0	38.5	32.9	0.90	0.82	0.66
B. Descriptive statistics						
Statistical variable	**Inclination angle (deg)**			**Symmetry index (-)**		
	Without orthosis	Foot-Up splint	Support strap	Without orthosis	Foot-Up splint	Support strap
Median	49.3	51.5	55.1	0.80	0.82	0.68
Q1	48.0	46.9	49.6	0.64	0.71	0.56
Q3	51.3	52.9	62.9	0.88	0.89	0.89

Table 1. Measured data **(A)** and descriptive statistics **(B)** of the inclination angle and symmetry index before and after the application of the Foot-Up splint and support strap.

the principal axis, i.e. inclination angle θ of angle-angle diagram, is obtained from the parameter α_1 as follows

$$tan\theta = \alpha_1. \quad (2)$$

For a better interpretation, we can visualize the data in modified synchronized bilateral cyclograms with the principal axis and "ideal" symmetry line, Figure 3. Circular marks on the trajectory, Figure 3, correspond to the moments of measurement, i.e. recording (sampling frequency is 60 Hz). Therefore, it is possible to directly read from the plotted cyclogram that the participant changed the values of the angles quickly or slowly. From a distance of the time-marks, which represent the instantaneous values of the angles, we see that the value of the angle is rapidly changed near the maximum and minimum knee angle. The Figure 3 shows the principal axis of the cyclogram i.e. the cyclogram's deviation from the "ideal" symmetry line. It is obvious that the principal axis of the cyclogram does not pass through the origin because the cyclogram can also be shifted.

The symmetry index (SI) was used as a comparative method to evaluate the symmetry of bipedal walking[32,33]. We used the "kinematic" symmetry index, also known as "symmetry ratio". The Symmetry Index is defined as the ratio of the joint angles on the non-paretic side to that on the paretic side. The index represents the difference between the range of motion (ROM), i.e. joint mobility, on the unaffected side and the range of motion (ROM) on the affected side. In case the value of the SI is one, the ranges of joint motions are equal on the left and right side of the body. In case of our study, the motion analysis involved determination of the ROM of the knee in the sagittal plane. Asymmetries in gait parameters were quantified using the following simple formula:

$$SI = \frac{ROM_{nom\text{-}paretic}}{ROM_{paretic}} \quad (3)$$

where ROM is the "range of motion" of the knee joint of non-paretic leg or paretic leg. The symmetry index is related to the maximum angles (i.e. maximum angle on right side and maximum angle on left side). After the measurements, the symmetry indexes and the inclination angles of cyclogram are calculated.

The principal axis of the bilateral cyclogram is inclined at an angle θ, the range of values is $0° \le \theta \le 90°$. The ideal inclination angle is 45°. The range of values of the symmetry index is $(-\infty, +\infty)$. The ideal symmetry index is SI=1. Unfortunately, the value of the inclination angle and symmetry index can be smaller or larger than the ideal value. Therefore, it is difficult to interpret the relationship between the inclination angle and the symmetry index. In order to determine the relationship between the inclination angle θ of cyclogram and "kinematic" symmetry index, we used a mathematical technique. The difference (i.e. cyclogram's deviation) of identified inclination angle of the bilateral cyclogram and ideal inclination angle is $\Delta\theta = |45° - \theta|$. Obviously, the greater the difference, the greater the asymmetry. For a better interpretation of the θ, it is suggested that if $\theta \le 45°$ then $\theta = 45° + \Delta\theta$, and thus $45° \le \theta \le 90°$. The difference of the identified SI and ideal SI is $\Delta SI = |1 - SI|$. Obviously, the greater the difference, the greater the asymmetry in ROM. For a better interpretation of the SI, it is suggested that if $SI \ge 1$ then $SI = 1 - \Delta SI$, and thus the range of values of the suggested SI is $(-\infty, 1)$.

Statistical analysis

After calculating the SI and θ of the synchronized bilateral knee-knee cyclograms of the participants without orthosis and with

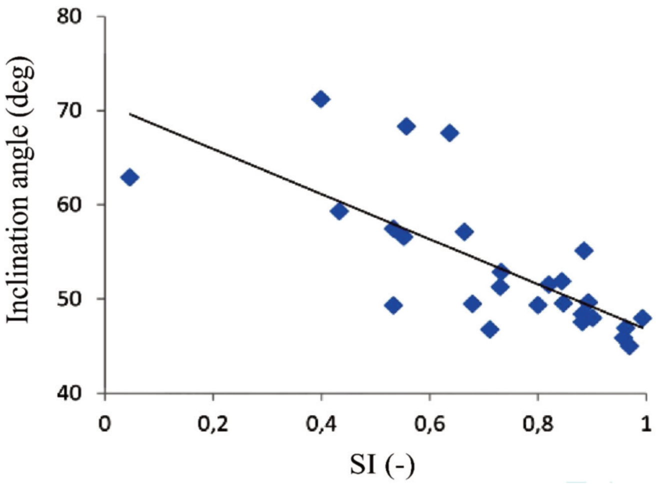

Figure 4. The relationship between the inclination angle and the symmetry index.

Foot-Up splint or support strap, the statistical analysis of these characteristics was also performed using the MatLab software.

First, we used the measured data (Table 1) to illustrate the relationship between the inclination angle and the symmetry index. We calculated the regression equation of the regression line, squared value (i.e. coefficient of determination) and Pearson product-moment correlation.

Second, we calculated the median, first quartile (Q1) and third quartile (Q3). We used the descriptive statistic to illustrate the relationship between the SI of the participants without orthosis and SI of the participants with Foot-Up splint or support strap, and between the θ of the synchronized bilateral knee-knee cyclograms of the participants without orthosis and θ of the participants with Foot-Up splint or support strap. The Jarque–Bera test (in MatLab software) was used to test the normal distribution of all parameters. The test returns the value h=1 if it rejects the null hypothesis at the 5% significance level, and h=0 if it cannot.

The data about the SI and θ of the synchronized bilateral knee-knee cyclograms of the participants without orthosis were compared with data about the SI and θ of the synchronized bilateral knee-knee cyclograms of the participants with Foot-Up splint and support strap. The Wilcoxon signed rank test was used to assess the significance of the differences between values obtained before and immediately after the application of the orthoses. The used two sample (paired) Wilcoxon signed rank test (a nonparametric test analogous to the paired t-test) tests the null hypothesis that the two samples come from measured data with the same median. The significance level was set at $p<0.05$.

Results

The following chart (Figure 4) shows the relationship between the inclination angle and the symmetry index (Table 1), where the regression equation of the regression line is $\theta=70.7-23.9\cdot SI$ and squared value (i.e. coefficient of determination) is 0.53. The Pearson product-moment correlation coefficient is -0.73. Correlation coefficient (-0.73) is statistically significantly different from zero and indicates a strong negative correlation between the inclination angle and symmetry index. The relationship between the SI and θ is evident, see Figure 4. The results also indicate that both methods (based on the inclination angle and symmetry index) show slightly different results.

The Jarque-Bera test returns h=1 in all cases. Since the data did not have a normal distribution, the Wilcoxon test was used to analyze this data. Participants with the Foot-Up splint did not demonstrate significant difference in SI (p=1.00) and inclination angle (p=0.82). Participants with the Support strap also did not demonstrate significant difference in SI (p=0.43) and inclination angle (p=0.20). All calculated p-values were greater than the significance level ($p<0.05$). Therefore, we do not reject the null hypothesis, and there is no significant difference between the data measured before and the data measured after the application of the orthoses. The data measured after the application of the support strap indicate the slight increase of the median of the inclination angle and slight decrease of the median of the symmetry index. It shows deterioration in gait symmetry, but it is negligible (according to the Wilcoxon signed rank test).

Discussion

The symmetry quantification technique based on the inclination angle of the synchronized bilateral knee-knee cyclograms is sensitive to the precision of synchronization of the two signals and the quality of the signals. As we can see from the examples above, it is not necessary to normalize the data because the angles used to evaluate the gait asymmetry are in degrees, and thus without the influence of the body height and weight of measured subject on the angles.

The methods based on the inclination angle and symmetry index show slightly different results. The reason of slightly different results is that the symmetry index depends on discrete variables and is unable to reflect the asymmetry as it evolves over a complete gait cycle. However, we can see the different sizes of joint angles during specific phases of the gait cycle and the irregular curve of bilateral cyclogram, Figure 2. The inclination angle of the synchronized bilateral knee-knee cyclogram depends on the complete gait cycle, i.e. evolutions of joint angles over time, see Figure 3.

The results also indicate that the new method based on cyclogram and method based on the SI did not identify significant improvement in the gait symmetry after the application of the Foot-Up splint or support strap. Although we expected some improvements in symmetry evaluated by symmetry index and inclination angle, the results are not conclusive. The participants were measured immediately after the application of orthopedic devices, and they were not accustomed to the orthoses. Also, the physician applied the orthoses without using a MoCap system, and only the ankle angles used to evaluate the walking performance. Therefore, the only immediate result of the application of orthoses is a very significant visual improvement in ankle joint function during the gait trials.

Also note that algebraic indices (i.e. SI) cannot be used to identify the gait asymmetry caused by a tremor or similar movement disorders because they compare only discrete variables such as maximum joint angles. On the other hand, the inclination angle also indicates the deviations of joint angles[13] caused, for example, by the mentioned tremor. However, it is necessary to create a synchronized bilateral cyclogram by using unfiltered measured data about the joint angles. Therefore, it is preferable to use an inclination angle of the synchronized bilateral knee-knee cyclograms to the study of patients with movement disorders.

Conclusions

The synchronized bilateral knee-knee cyclograms inform us about the gait symmetry and this information could be important in rehabilitation medicine, and also could be used in control algorithms for lower limb prostheses or bipedal robots. For the purposes of locomotion therapy[34], a new software system could use the method for a driven robotic gait orthosis. This work has not attempted to describe all potential ways of applying the inclination angle of the synchronized bilateral knee-knee cyclograms. We have shown new method that has subsequently been tested on participants with peroneal nerve palsy. Our results indicate that the new method based on cyclogram and method based on the SI did not identify significant improvement in the gait symmetry after the application of the orthoses. It is expected that after a long application time of the orthoses, the participants will get used to the orthoses, and posture and gait will be improved. In the future study, we plan to measure more participants with other types of orthoses, and evaluate the gait symmetry during a longer period of therapy.

Acknowledgement

The work presented here was carried out at the Czech Technical University in Prague, Faculty of Biomedical Engineering within the framework of research program No. SGS13/091/OHK4/1T/17.

References

1. Gage RJ, Hicks R. Gait Analysis in Prosthetics. Clinical Prosthetics & Orthotics 1989;9:17-21.
2. Janura M, Cabell L, Svoboda Z, Kozakova J, Gregorkova A. Kinematic analysis of gait in patients with juvenile hallux valgus deformity. Journal of Biomechanical Science and Engineering 2008;3:390-98.
3. Koktas NS, Yalabik N, Yavuzer G. Combining neural networks for gait classification. Proc. of the 11th Iberoamerican Congress on Pattern Recognition, Mexico, Cancun; 2006;11:381-88.
4. Sepulveda F, Wells D, Vaughan C. A neural network representation of electromyography and joint dynamics in human gait. J Biomech 1993;26:101-9.
5. Heller BW, Veltlink PH, Rijkhof NJM, Rutten WLC. Andrevs B. Reconstructing muscle activation during normal walking: a comparison of symbolic and connectionist machine learning techniques. Biol Cybern 1993;69:327-35.
6. Arsenault AB, Winter DA, Marteniuk RG. Bilateralism of EMG profiles in human locomotion. Am J Phys Med Rehabil 1986;65:1-16.
7. Grieve DW. Gait patterns and the speed of walking. Biomed Eng 1968;3:119-22.
8. Grieve DW. The assessment of gait. Physiotherapy 1969; 55:452-60.
9. Kutilek P, Viteckova S. Prediction of Lower Extremity Movement by Cyclograms. Acta Polytechnica 2012; 52:51-60.
10. Hajny O, Farkasova B. A Study of Gait and Posture with the Use of Cyclograms. Acta Polytechnica 2010;50:48-51.
11. Giannini RC, Perell KL. Lower limb coordination during walking in subjects with post stroke hemiplegia vs. healthy control subjects. Clinical Kinesiology 2005; 59:63-70.
12. Heck A, Holleman A. Walk like a mathematician: an example of authentic education. Proc. of ICTMT6, Greece, Athens 2003;6:380-387.
13. Goswami A. Kinematics quantification of gait symmetry based on bilateral cyclograms. Proc. of the XIXth Congress of the International Society of Biomechanics (ISB), New Zealand, Dunedin; 2003.
14. Herzog W, Nigg BM, Read LJ, Olsson E. Asymmetries in ground reaction force patterns in normal human gait. Med Sci Sport Exer 1989;21:110-14.
15. Vogt L, Banzer W, Bayer I, Schmidtbleicher D, Kerschbaumer F. Overground and walkway ambulation with unilateral hip osteoarthritis: comparison of step length asymmetries and reproducibility of treadmill mounted force plate readings. Physiotherapy Theory and Practice 2006;22:73-82.
16. Roerdink M, Beek PJ. Understanding inconsistent step-length asymmetries gross hemiplegic stroke patients: impairments and compensatory gait. Neurorehab Neural Re 2011;25:253-58.
17. Pierotti SE, Brand RA, Gabel RH, Pedersen DR, Clarke WR. Are leg electromyogram profiles symmetrical? J Orthop Res 1991;9:720-29.
18. Goswami A. New Gait Parameterization Technique by Means of Cyclogram Moments: Application to Human Slope Walking. Gait and Posture 1998;8:15-26.
19. Kutilek P, Farkasova B. Prediction of Lower Extremities Movement by Angle-Angle Diagrams and Neural Networks, Acta of Bioengineering and Biomechanics 2011; 13:57-65.
20. Goldstein H. Classical Mechanics (2nd ed.). Boston: Addison-Wesley; 1980.
21. Garosso D, Ferraresi S, Buffatti P. Common peroneal nerve palsy complicating ankle sprain: report of 5 cases and review of the literature. J Orthopaed Traumatol 2003; 4:142-45.
22. Masakado Y, Kawakami M, Suzuki K, Abe L, Ota T,

Kimura A. Clinical neurophysiology in the diagnosis of peroneal nerve palsy. Keio J Med 2008;2:84-89.
23. Wong M, Wong D, Wong A. A Review of Ankle Foot Orthotic Interventions for Patients with Stroke. The Internet Journal of Rehabilitation 2010;1:1.
24. Öberg T, Karsznia A, Oberg K. Joint angle parameters in gait: Reference data for normal subjects, 10-79 years of age. J Rehab Res Dev 1994;31:199-213.
25. Menache A. Understanding Motion Capture for Computer Animation. Burlington: Morgan Kaufmann; 2011.
26. Liebensteiner MC, Szubski C, Raschner C, Krismer M, Burtscher M, Platzer HP, Deibl M, Dirnberger E. Frontal plane leg alignment and muscular activity during maximum eccentric contractions in individuals with and without patellofemoral pain syndrome. Knee 2008;15:180-6.
27. Sehle A, Mündermann A, Starrost K, Sailer S, Becher I, Dettmers C, Vieten M. Objective assessment of motor fatigue in Multiple Sclerosis using kinematic gait analysis: a pilot study. J Neuroeng Rehabil 2011;8:59.
28. Kutilek P, Hajny O. Study of Human Walking by SimMechanics. Proc. of the 18th Technical Computing, Slovakia, Bratislava; 2010.
29. Kutilek P, Hozman J. Prediction of lower extremities movement using 32 characteristics of angle-angle diagrams and artificial intelligence. Proc. of the 3rd International Conference on E-Health and Bioengineering (EHB 2011), Romania, Iasi; 2011.
30. O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL. Automatic detection of gait events using kinematic data. Gait Posture 2007;25:469-74.
31. Seber G, Lee A. Linear Regression Analysis. New York: John Wiley & Sons, Inc., 1977.
32. Zifchock RA, Davis I, Higginson J, Royer T. The symmetry angle: A novel, robust method of quantifying asymmetry. Gait Posture 2008;27:622-27.
33. Horvath M, Tihanyi T, Tihanyi J. Kinematic and kinetic analyses of gait patterns in hemiplegic patients. Phys Educ Sport 2001;8:25-35.
34. Boian FR, Burdea CG, Deutsch EJ. Robotics and Virtual Reality Applications in Mobility Rehabilitation. In: Aleksandar Lazinica editor. Rehabilitation Robotics. Vienna: I-Tech Education and Publishing; 2007. p.27-42.