

Imbalanced Gait Characteristics Based on Plantar Pressure Assessment in Patients with Hemiplegia

Suwaporn SANGHAN¹, Wipawan LEELASAMRAN² and Surapong CHATPUN^{1,*}

¹*Institute of Biomedical Engineering, Faculty of Medicine, Prince of Songkla University, Songkhla 90110, Thailand*

²*Department of Orthopaedic Surgery and Physical Medicine, Faculty of Medicine, Prince of Songkla University, Songkhla 90110, Thailand*

(*Corresponding author's e-mail: surapong.c@psu.ac.th)

Received: 13 March 2014, Revised: 21 September 2014, Accepted: 12 October 2014

Abstract

This study aimed to assess the plantar pressure and the gait characteristics in patients with hemiplegia compared with normal subjects. Plantar pressure was measured and evaluated by the Pedar-x system[®]. Twenty healthy Thai volunteers and 10 Thai patients with hemiplegia were recruited for this study. Patients with hemiplegia had significant differences in gait pattern and plantar pressure distribution compared with normal subjects. The percentages of the plantar pressure difference were 5 ± 3 and 30 ± 12 % in the normal group and the hemiplegic group, respectively. The time interval during single limb support on the affected side was 11 % shorter than the unaffected side while there was no difference of the time interval during single limb support in normal subjects. The pattern and area under the curve of normalized force-time relationship in patients with hemiplegia were particularly distinguishable from normal subjects. The progression lines of both feet were asymmetric in patients with hemiplegia but they were particularly symmetric in normal subjects. The gait characteristics derived from plantar pressure in patients with hemiplegia are apparently imbalanced and clearly different from that in normal subjects in both qualitative and quantitative aspects.

Keywords: Plantar pressure, hemiplegia, gait cycle, gait line, ground reaction force

Introduction

Patients with hemiplegia resulting from cerebrovascular diseases commonly demonstrate one or more deviations from the normal walking kinematics [1,2]. Hemiplegia, a paralysis of one side of body, is the sign of neurovascular disease of the brain, and is the most common impairment after a stroke which reduces gait performance [3]. Hemiplegia is a major concern for physical therapists and it is always an obvious sign of cerebrovascular disease, including sensory dysfunction, aphasia, visual field defects and mental and intellectual impairment. The factors of hemiplegia leading to gait disorder are varied and depend on the severity of the disease, the location of the damage in the brain and the duration of impairment [4]. Hemiplegic patients have a variation and unbalanced walk, including altered ground reaction forces. Plantar pressure measurement is one of the useful methods that can be used to assess the gait abnormality of patients [5-7].

Various quantification methods with different technologies have been introduced for foot pressure analysis such as in-shoe system and capacitive pressure distribution platform [4,7-9]. The Pedar-x system[®], an in-shoe dynamic vertical pressure measuring system, has a good repeatability and a high accuracy in plantar pressure measurement in many conditions as reported in several studies [10-14]. Pedar-x system[®] measures pressure applied to each sensor embedded in the insole. In addition, the Pedar-x system[®] can be used to evaluate disorders in gait and correlated to foot pathologies [11]. Recently,

Waaajman and colleagues have used the Pedar-x system[®] to study plantar pressure on diabetic foot ulcerations [15]. They have reported that the maximum peak pressure is interchangeable with pressure-time integral in the diabetic footwear study.

Plantar pressure is an interesting parameter to use for the gait dysfunction diagnosis. It also can be used to evaluate and quantify gait characteristics of patients with hemiplegia. However, there are still no conclusions on characteristics that can be applied for monitoring of rehabilitation progress relative to normal people or use for training devices for patients with hemiplegia. We also previously did a preliminary study on the plantar pressure distribution with only 5 Thai patients with hemiplegia [16]. However, it still requires an increasing number of patients. Therefore, this study increased the number of patients and focused on the assessment of the plantar pressure and the evaluation of the gait characteristics during walking between hemiplegic and normal subjects. The understanding of the differences in gait characteristics between patients with hemiplegia and normal subjects can be utilized to develop feedback assistive walking devices based on plantar pressure derived parameters for patients with hemiplegia or to create a rehabilitation program for them.

Materials and methods

Participants

Twenty normal subjects and 10 patients with hemiplegia were recruited from the university medical school center. All participants read and signed an informed consent, which was approved by the ethics committee of the faculty of medicine, Prince of Songkla University (EC-54-264-25-6-3). Normal subjects without a history of surgery or history of trauma or leg length discrepancy and over 40 years old were included in this study. Patients with a history of hemiparesis who were older than 40 years of age and able to walk without using any walking aids were included in this study. Hemiplegic patients who had a stroke from 3 months to 6 years earlier were studied. **Table 1** shows the demographic data of subjects involved in this study.

Study protocol

All participants were asked, each time, to walk naturally with their own sport shoes along a 10 m walkway for 3 rounds. At the end of each round, subjects took a rest for 3 min before starting to walk again. All participants had to repeat this 3 times.

Table 1 Demographic data of participants.

Demographics	Normal person		Patient with hemiplegia	
	Male	Female	Male	Female
Number of subjects	10	10	5	5
Affected side	-	-	5 L	2 L / 3 R
Age (years)	46 ± 4	47 ± 5	61 ± 13	53 ± 6
Body weight (kg)	63.97 ± 5.74	55.27 ± 7.23	73.20 ± 10.76	59.80 ± 5.54
Height (m)	1.66 ± 0.06	1.55 ± 0.05	1.65 ± 0.06	1.54 ± 0.05
Body mass index (kg/m ²)	23.12 ± 1.03	23.07 ± 2.99	26.80 ± 2.98	25.74 ± 1.47

Values are in mean ± SD, L and R in affected side means left and right.

Plantar pressure measurement and data analysis

Plantar pressure was measured and determined using the Pedar-x system[®] (Novel GmbH, Munich, Germany). The insole has an array of 99 capacitive sensors and 4 insole sizes (size U = Asian shoe size 22.5 - 23.5, size V = Asian shoe size 24 - 25.5, size W = Asian shoe size 26 - 26.5 and size X = Asian shoe size 27 - 27.5) were used to accommodate 4 different foot sizes. The 2.6 mm thick insoles were

inserted into the shoes and connected to the Pedar[®] box (A/D converter). The system was calibrated under the manufacturer's instructions before starting the measurement. The plantar pressure measurement was acquired with a minimum sample rate that was preset in the system i.e. at 50 Hz for U and V insole sizes for females and 100 Hz for W and X insole sizes for males. The Pedar-x system[®] has an inbuilt threshold of 15 kPa, resulting in a cut-off value in pressure recording. This threshold was also used clinically to reduce noise when recording in-shoe data [8].

The plantar pressure was analyzed using Novel Database Essential software version 12.3. We further calculated the percentage of plantar pressure difference (PPD) from the mean value pressure of each side as expressed in Eq. (1) proposed by Sanghan *et al.* [16]. In addition, the percentage of phases in a gait cycle, the temporal-force normal to the plantar surface relationship and its area under the curve, the center of pressure (COP) progression line and the foot progression angle [17,18] were determined.

$$\text{Percentage of plantar pressure difference (PPD)} = \frac{2 \left| \text{Pressure}_{\text{Left}} - \text{Pressure}_{\text{Right}} \right|}{\text{Pressure}_{\text{Left}} + \text{Pressure}_{\text{Right}}} \times 100 \quad (1)$$

Statistical analysis

All data were statistically analyzed and presented as mean $\pm$ standard deviation (SD). Mann Whitney tests were performed to compare the percentage of plantar pressure difference, the percentage of phases in a gait cycle, the area under the curve of the force-time relationship and the foot progression angle. Statistical analysis was performed using Prism 5.0 for Windows (GraphPad Software, San Diego, USA). Differences were considered to be significant at a *p*-value less than 0.05.

Results and discussion

Plantar pressure

Plantar pressure distribution was distinctively different between normal and hemiplegic groups. **Figure 1** (top) illustrates an example of the normal sequence of plantar pressure during walking; representing a smooth pressure transfer from the heel (a), to the lateral midfoot (c), to the metatarsophalangeal area (d), to the toes (e) and finally to the hallux before going into the swing phase period. We found that the plantar pressure distribution on the left side was not much different from the right side in normal subjects. Whereas in patients with hemiplegia as shown in **Figure 1** (middle and bottom), the plantar pressure on the affected side had a lower magnitude compared with normal subjects. On the affected side of patients, the plantar pressure on the regions of the midfoot, metatarsophalangeal and hallux was less than that of normal persons. The significant difference in plantar pressure when compared between normal and hemiplegic subjects was similar to the previous study that showed the plantar dynamics had a difference on the uninvolved leg of the patients [19]. Furthermore, there was a significant difference in the percentage of plantar pressure difference (PPD) between the groups (*p* < 0.05). The value of PPD in the normal group and the hemiplegic group were 5 ± 3 and 30 ± 12 %, respectively. This difference showed unequal force normal to the plantar surface acting on the foot in the patients. Furthermore, the higher PPD might be useful to indicate the severity of hemiplegia.

Percentage of phases in a gait cycle

The gait cycle has been divided into 8 functional patterns; (i) initial contact, (ii) loading response, (iii) mid stance, (iv) terminal stance, (v) pre-swing, (vi) initial swing, (vii) mid swing and (viii) terminal swing as described in a previous study [20]. The percentage of phases in a gait cycle in the normal group and the hemiplegic group are shown in **Figure 2**. The time period of the 1st double limb support was similar to the 2nd double limb support in normal subjects. The period of single limb support in both left and right sides were also similar in the normal group. In contrast, the percentage of phases in a gait cycle in patients with hemiplegia was significantly different between a single limb support of the affected side and that of the unaffected side (*p* < 0.05). The single limb support on the unaffected side took a longer

period than that on the affected side. In the hemiplegic group, there was also a significant difference between the periods of 1st double limb support and 2nd double limb support ($p < 0.05$). Our results are in agreement with Pizzi and colleagues [21] who found that the asymmetrical gait of patients with hemiplegia showed less time was spent on the affected limb than that on the unaffected limb during the single limb support phase. Normally, the 2 periods of double limb and single limb support time intervals are symmetrical in normal persons [22]. In our study, the time intervals of single limb support between affected and unaffected sides were significantly different. On the affected side, the time period was shorter than the unaffected side due to the weakness of functional muscles [23,24]. Woolley also reported that the gait patterns in patients with hemiplegia differ from that in normal healthy participants because there was a lack of bilateral symmetry [19].

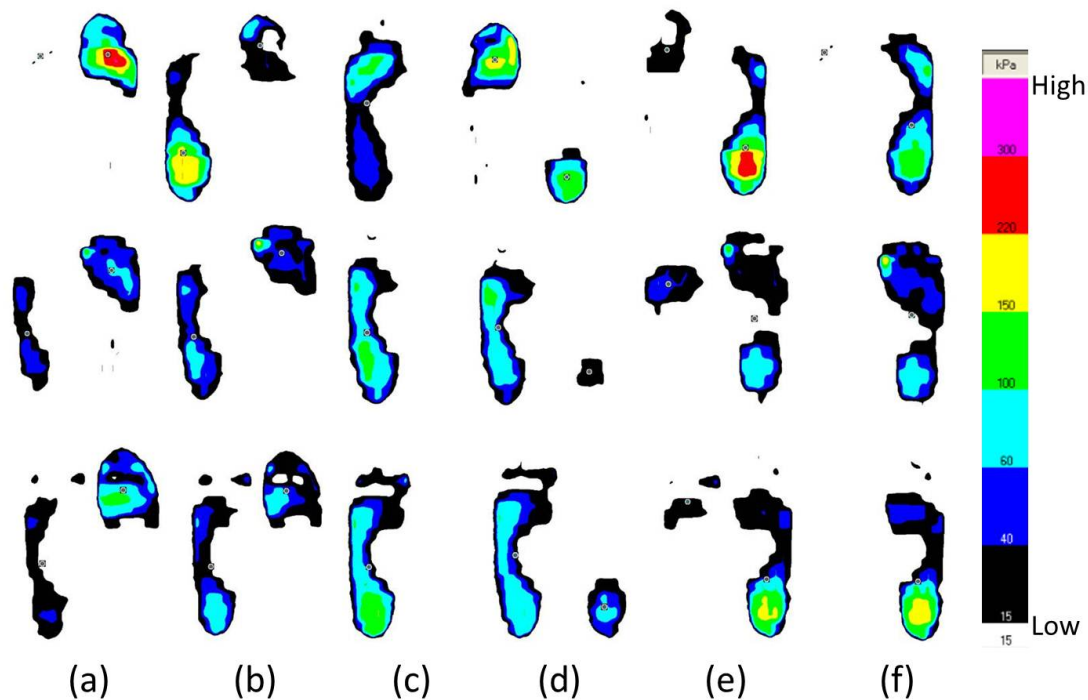


Figure 1 Examples of plantar pressure distribution during walking in fundamental phases of human gait in a normal person (top) and patients with hemiplegia (middle and bottom). Gait phases: Initial contact (a); Midstance (b), (c) and (d); Propulsion (e); Swing (f). High represents pressure > 300 kPa and Low represents pressure < 15 kPa.

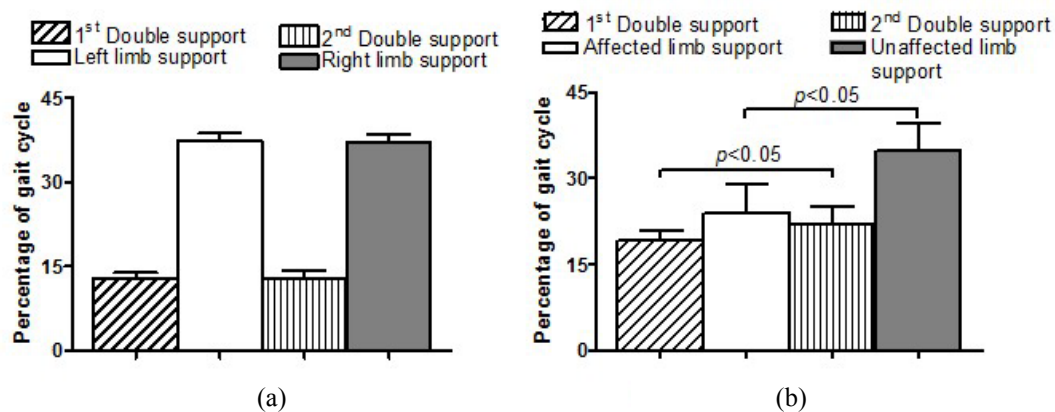


Figure 2 Percentage of phases in the gait cycle in (a) normal and (b) hemiplegic subjects classified into single limb support and double limb support.

Force normal to plantar surface

The examples of the force normal to the plantar surface normalized with body weight in time domain are presented in **Figures 3a** and **3b**. During normal gait, the curve of the normalized force perpendicular to the plantar surface looked like an M-shape curve, showing good symmetry between right and left sides. In contrast, patients with hemiplegia presented an asymmetric pattern of the force normal to the plantar surface in both affected and unaffected sides. As a result, the curve of the affected side showed an irregular shape and was narrower when compared with the unaffected side. Furthermore, the normalized force and the ground contact time on the affected side were less than the unaffected side. The hemiplegic patients have an abnormal pattern of force normal to the plantar surface because of the reduction in loading force related to poor confidence, discomfort, and poor functional movement of the lower limb on the affected side [25]. The time per a gait cycle was longer in hemiplegic subjects than normal subjects. The percentage of the difference between the areas under the curve (AUC) of the force-time relationship is presented in **Figure 3c**. The difference of AUC in hemiplegic patients was significantly greater than that in normal subjects ($p < 0.05$). It means that the patients with hemiplegia used less amplitude of force on the affected side and the time on the affected single support was particularly short. Therefore, the difference between in the AUC of the force-time relationship can be used as a quantitative indicator to evaluate the walking ability of patients with hemiplegia.

Center of pressure progression line

The progression line, the pathway of center of pressure (COP), can be used as a measure of the personal ability to maintain balance. We observed the COP progression line during the gait cycle. It was found that, in a normal gait, the COP moved from the heel at initial contact along the foot to the big toe as shown in **Figure 4a**. The length of the progression line between the left and right sides of normal persons was clearly different to that of patients with hemiplegia. We found that the gait progression line on the affected side was shorter than the unaffected side in patients with hemiplegia and this line showed an asymmetry between left and right sides (**Figures 4b** and **4c**). Rodgers and colleagues reported that the length of the COP path or gait progression line in patients with hemiplegia was short and asymmetric, which was similar to our results [26].

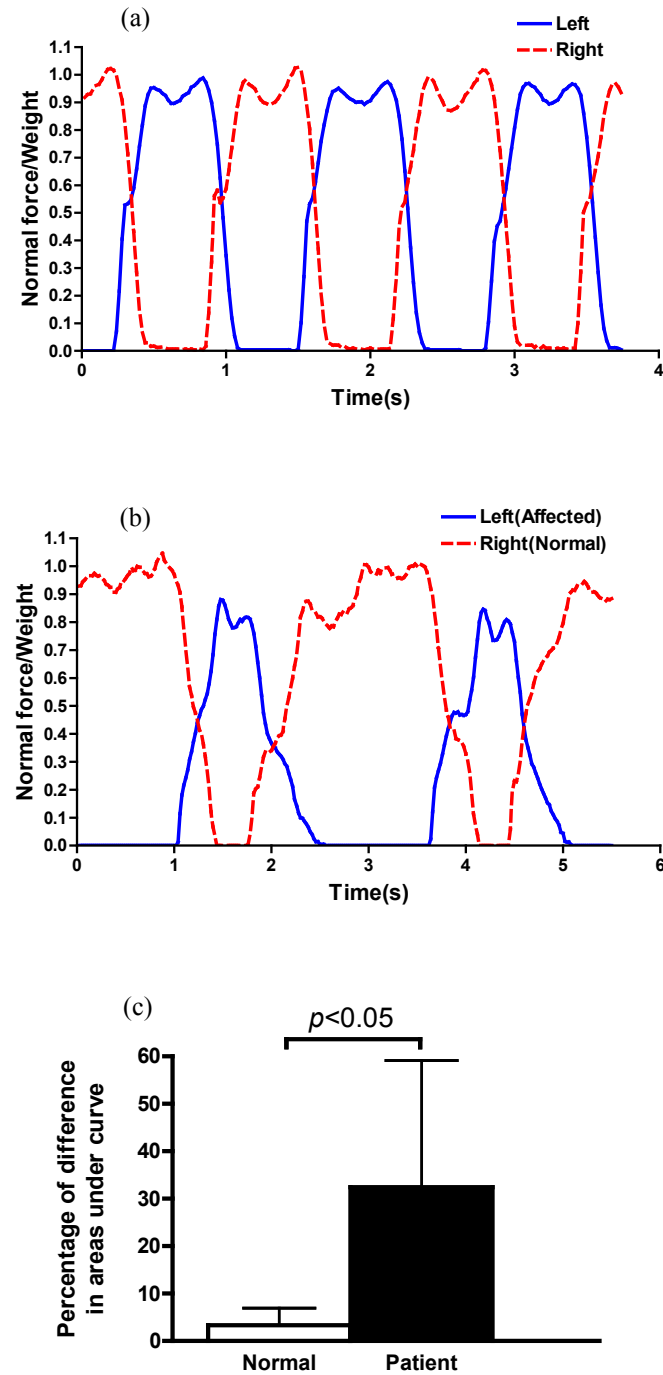


Figure 3 Example of the normalized force-time relationships in (a) normal subject, (b) patient with hemiplegia, (c) the percentage difference of the areas under the curve in a normalized force-time relationship.

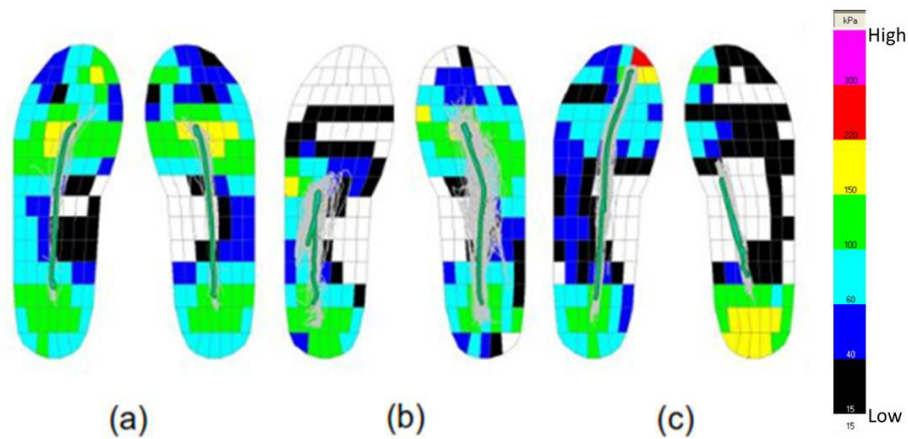


Figure 4 Examples of COP progression lines in (a) a normal person, (b) affected left side and (c) affected right side of patients with hemiplegia. High represents pressure > 300 kPa and low represents pressure < 15 kPa.

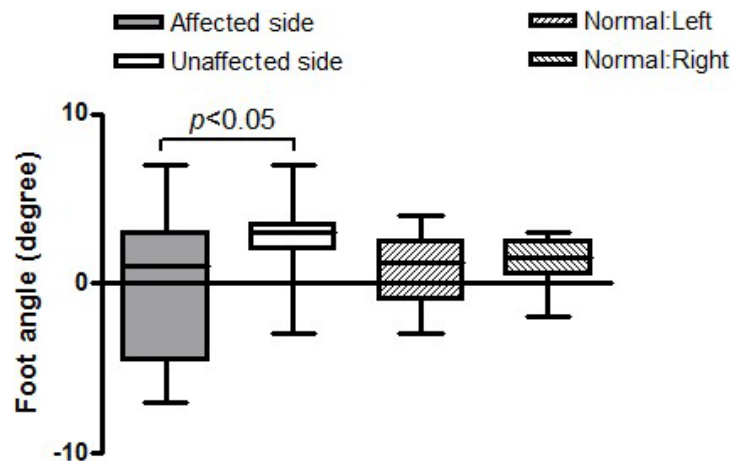


Figure 5 Foot progression angles in normal subjects and patients with hemiplegia.

Foot progression angle

The foot progression angle describes the degree of in-toeing or out-toeing of the foot relative to the forward line of progression and demonstrates the pressure distribution behavior, in a walking pattern [27]. **Figure 5** shows that foot angle values in normal subjects are in the range of -2 to +4 degrees (Left: median 1.25, 25 % percentile -1.0 and 75 % percentile 2.5; Right: median 1.5, 25 % percentile 0.5 and 75 % percentile 2.5); whereas hemiplegic foot angle values are in the range of -7 to +7 degrees on the affected side (median 1.0, 25 % percentile -4.5 and 75 % percentile 3.0) and -3 to -7 degrees on the unaffected side (median 3.0, 25 % percentile 2.0 and 75 % percentile 3.5;). We found the foot angle values of the affected side were significantly less than that of the unaffected side ($p < 0.05$). It is also noteworthy that the range of foot progression angle values was very wide on the affected side. In contrast, in normal subjects, there was no difference in the foot progression angle values when compared between the left and right sides.

This study has clearly demonstrated and characterized plantar pressure assessment, with the walking condition of patients with hemiplegia. The results of this study provided evidence to support the different gait characteristics between normal people and patients with hemiplegia. Moreover, our investigation looked at and evaluated the differences in gait characteristics related to plantar pressure between normal subjects and patients with hemiplegia. Then the effective and practical parameters can be used as a criteria input or threshold values for hemiplegic patient's rehabilitation devices to do gait training or to monitor the progress of rehabilitation on the affected side.

Conclusions

In conclusion, our results showed that patients with hemiplegia had distinctly different gait characteristics from normal subjects in 5 main ways; the unequal plantar pressure distribution between both sides, the difference in the percentage of gait cycle in the single limb support, the lower non-smooth peak and irregular pattern of the force-time relationship curve, the asymmetric progression line and the wide range of foot progression angle values. These characteristics will be useful to use as threshold settings for walking assistive devices for patients with hemiplegia.

Limitations

Our study had several limitations. First, the number of patients in our study, only 10 patients, was still considerably small compared to other studies [2,4]. Therefore, if the number of patients increases we can obtain more precise and effective information. Second, the foot type was not assessed in the process of participant selection before the measurement. Several studies reported that flat foot types have decreased peak pressure compared with normal foot types [28,29]. Third, patients with hemiplegia had different clinical features due to the degree and duration of disability, cause of stroke, degree of severity, age of patient and physical therapy service.

Acknowledgements

The authors would like to thank the volunteers and patients in their contribution to this study. The authors would like to thank Ms. Suwicha Techaphuwapat for technical discussion and Mr. David Leather for editing assistance. This work was supported by the research funding from the faculty of medicine, Prince of Songkla University grant number 54-264-25-6-3.

References

- [1] A Moseley, A Wales, R Herbert, K Schurr and S Moore. Observation and analysis of hemiplegic gait: Stance phase. *Aust. J. Physiother.* 1993; **39**, 259-67.
- [2] EJ Roth, C Merbitz, K Mroczek, SA Dugan and WW Suh. Hemiplegic gait. Relationships between walking speed and other temporal parameters. *Am. J. Phys. Med. Rehabil.* 1997; **76**, 128-33.
- [3] JM Belda-Lois, SM Horno, I Bermejo-Bosch, J Moreno, J Pons, D Farina, M Iosa, M Molinari, F Tamburella, A Ramos, A Caria, T Solis-Escalante, C Brunner and M Rea. Rehabilitation of gait after stroke: A review towards a top-down approach. *J. Neuro Eng. Rehabil.* 2011; **8**, 66.
- [4] S Meyring, RR Diehl, TL Milani, EM Hennig and P Berlit. Dynamic plantar pressure distribution measurements in hemiparetic patients. *Clin. Biomech.* 1997; **12**, 60-5.
- [5] MN Orlin and TG McPoil. Plantar pressure assessment. *Phys. Ther.* 2000; **80**, 399-409.
- [6] V Femery, P Moretto, H Renaut, A Thevenon and G Lensel. Measurement of plantar pressure distribution in hemiplegic children: Changes to adaptative gait patterns in accordance with deficiency. *Clin. Biomech.* 2002; **17**, 406-13.
- [7] R Schuh, JG Hofstaetter, SG Hofstaetter, SB Jr. Adams, KH Kristen and HJ Trnka. Plantar pressure distribution after tibiotalar arthrodesis. *Clin. Biomech.* 2011; **26**, 620-5.

- [8] S Barnett, JL Cunningham and S West. A comparison of vertical force and temporal parameters produced by an in-shoe pressure measuring system and a force platform. *Clin. Biomech.* 2001; **16**, 353-7.
- [9] M Birtane and H Tuna. The evaluation of plantar pressure distribution in obese and non-obese adults. *Clin. Biomech.* 2004; **19**, 1055-9.
- [10] HLP Hurkmans, JBJ Bussmann, RW Selles, HLD Horemans, E Benda, HJ Stam and JAN Verhaar. Validity of the Pedar Mobile system for vertical force measurement during a seven-hour period. *J. Biomech.* 2006; **39**, 110-8.
- [11] AK Ramanathan, P Kiran, GP Arnold, W Wang and RJ Abboud. Repeatability of the Pedar-X® in-shoe pressure measuring system. *Foot Ankle Surg.* 2010; **16**, 70-3.
- [12] Z Pataky, DL Rodriguez, L Allet, A Golay, M Assal, JP Assal and CA Hauert. Biofeedback for foot offloading in diabetic patients with peripheral neuropathy. *Diabet. Med.* 2010; **27**, 61-4.
- [13] HLP Hurkmans, JBJ Bussmann, E Benda, JAN Verhaar and HJ Stam. Accuracy and repeatability of the Pedar Mobile system in long-term vertical force measurements. *Gait Posture* 2006; **23**, 118-25.
- [14] AB Putti, GP Arnold, L Cochrane and RJ Abboud. The Pedar® in-shoe system: Repeatability and normal pressure values. *Gait Posture* 2007; **25**, 401-5.
- [15] R Waaijman, ML Arts, R Haspels, TE Busch-Westbroek, F Nollet and SA Bus. Pressure-reduction and preservation in custom-made footwear of patients with diabetes and a history of plantar ulceration. *Diabet. Med.* 2012; **29**, 1542-9.
- [16] S Sanghan, S Chatpun and W Leelasamran. Gait characterizations under dynamic load during walking in hemiplegic patients. In: *Proceedings of the Biomedical Engineering International Conference 2011*. Chiangmai, Thailand, 2011. p. 22-5.
- [17] NL Keijsers, NM Stolwijk, B Nienhuis and J Duysens. A new method to normalize plantar pressure measurements for foot size and foot progression angle. *J. Biomech.* 2009; **42**, 87-90.
- [18] TW Kernozek and MD Ricard. Foot placement angle and arch type: effect on rearfoot motion. *Arch. Phys. Med. Rehabil.* 1990; **71**, 988-91.
- [19] SM Woolley. Characteristics of gait in hemiplegia. *Top. Stroke Rehabil.* 2001; **7**, 1-18.
- [20] K Kyoungchul and M Tomizuka. Estimation of abnormalities in a human gait using sensor-embedded shoes. In: *Proceedings of the International Conference on Advanced Intelligent Mechatronics 2008*, Xian, 2008, p. 1331-6.
- [21] A Pizzi, G Carlucci, C Falsini, F Lunghi, S Verdesca and A Grippo. Gait in hemiplegia: Evaluation of clinical features with the Wisconsin gait scale. *J. Rehabil. Med.* 2007; **39**, 170-4.
- [22] C Kirtley. *Clinical Gait Analysis Theory and Practice I*. Elsevier, Washington DC, USA, 2006.
- [23] JJ Eng, CM Kim and DL Macintyre. Reliability of lower extremity strength measures in persons with chronic stroke. *Arch. Phys. Med. Rehabil.* 2002; **83**, 322-8.
- [24] CM Kim and JJ Eng. The relationship of lower-extremity muscle torque to locomotor performance in people with stroke. *Phys. Ther.* 2003; **83**, 49-57.
- [25] J Richards. *Biomechanics in Clinic and Research: An Interactive Teaching and Learning Course*. 1st ed. Churchill Livingstone, 2008.
- [26] MM Rodgers, L Forrester, C Mizelle and M Harris-Love. Effects of gait velocity on COP symmetry measures in individuals with stroke. In: *Proceedings of the 28th Annual Meeting of American Society of Biomechanics*. Portland, Oregon, 2004.
- [27] K Nawata, S Nishihara, I Hayashi and R Teshima. Plantar pressure distribution during gait in athletes with functional instability of the ankle joint: preliminary report. *J. Orthop. Sci.* 2005; **10**, 298-301.
- [28] HW Chang, HF Chieh, CJ Lin, FC Su and MJ Tsai. The relationships between foot arch volumes and dynamic plantar pressure during midstance of walking in preschool children. *Plos One* 2014; **9**, e94535.
- [29] B Chuckpaiwong, JA Nunley, NA Mall and RM Queen. The effect of foot type on in-shoe plantar pressure during walking and running. *Gait Posture* 2008; **28**, 405-11.