Fiber Optic-based Insole Development to Estimate the Gait Subphases

Daniel Eduardo García Álvarez

Research Internship

Supervisor:
Prof. PhD. Oscar Perdomo

UNIVERSIDAD DEL ROSARIO
ESCUELA COLOMBIANA DE INGENIERÍA JULIO GARAVITO
BIOMEDICAL ENGINEERING PROGRAM
BOGOTÁ D.C
2023

ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisors Óscar Perdomo and Thomas Provot for guiding me and sharing their knowledge with me during this process. Besides, to my professors and good friends Carlos Cifuentes and Marcela Múnera, for making a dream become a reality, for allowing me to live a great personal and professional experience and for always trusting in me. To Sergio Sierra for always being a strong support, giving me his help when I needed it and for letting me be part of Team Walker. And finally, to my mother Asseneth Alvarez for being a fundamental part and my motivation in this journey, and to my father Diego Garcia, without him none of this would have been possible.

TABLE OF CONTENT

1. INTRODUCTION

Human gait is a complex process of the locomotor system that allows the displacement of the body through the coordinated and alternated action of the lower limbs [1], [2]. Different neurological pathologies such as Stroke (ST), Spinal Cord Injuries (SCI), Cerebral Palsy (CP), and even neurodegenerative disorders like Parkinson's disease (PD), Multiple Sclerosis (MS), and Huntington's disease (HD), considerably affect balance, stability and motor skills during this process [1], [3], [4]. According to the World Health Organization (WHO), these conditions could represent the second leading cause of death worldwide in 2030 [5]. Besides, they indicate that the proportion of people with mobility impairments has progressively increased, reaching 15% of the world's population [6].

This scenario has prompted multidisciplinary teams of engineers and healthcare professionals to develop several devices and strategies to provide appropriate gait training and rehabilitation [7]. Concretely, the use of robots such as portable ankle orthoses and lower limb exoskeletons has been extensively explored [8], [9]. These wearable structures assist joint movement and, in many instances, have been shown to increase motor skills [10].

However, due to the increased use of these devices as an alternative for gait rehabilitation, gait sub-phase detection has become a challenge and an increasingly important feature in the control of these robots [11]. Currently, these phases can be captured using a variety of devices. On the one hand, the accuracy standard for walking kinematics is defined by non-wearable sensors like force platforms and video-based motion capture systems [12]. These sensors are expensive and can only be used indoors [13]. For this and due to their accessibility, quicker donning/doffing times, and simpler post-processing, wearable sensors such as ultrasonic sensors [14], electromyography (EMG) signals [15], footswitches [16], [17] and inertial sensors [18], [19] have gained popularity. Although they are promising technologies, one of their disadvantages is the high cost and the recalibration problems during trials.

On the other hand, since each gait phase can be connected to a specific pressure pattern [20], [21], foot pressure insoles or footswitches are thought to be the best detection option among wearable sensors intended for gait segmentation. Additionally, the footswitch-based reference has been widely used to identify gait events [22], [23]. For flexible pressure sensors that can be used in insoles, piezoresistive sensors and force-sensitive resistor polymer thick films exhibit changing resistances in response to pressure, are reasonably priced, and have a practical input composition [24]. However, their use in routine activities is not advised since they must be positioned in the best places to reliably detect gait phases, necessitating the assistance of an expert [25]. Besides, these sensors may have limitations such as electrical interference, low spatial resolution, and pressure range [26].

This way, fiber optic sensors exhibit numerous advantages related to (1) high sensitivity, (2) resolution, and (3) dynamic range. Besides, these sensors offer immunity to radio frequency interference and electromagnetic interference and can perform in harsh environments where conventional electrical sensors have difficulties [27] Because of these advantages, fiber optic sensors have been implemented in force measurement devices such as insoles and platforms [28].

Domingues et al. presented an insole optical fiber to monitor the vertical force (VF) during gait and body center of mass displacements, reporting a sensitivity of 11.06 pm/N during vertical force measurements. Specifically, this force can be used to find abnormalities and pathologies in gait [29]. Lakho et al. analyzed the distribution of plantar pressures during different tasks, focusing on the Metatarsal and heel sections. This study found linear behavior in the VF measurement employing a fiber optic sensor [30]. Additionally, [31] presents a fiber-optic-based insole with an innovative technique, which apart from monitoring foot pressure, implements the force signal to identify the different sub-phases of gait. Notwithstanding, current applications have major limitations during the calibration process that can significantly affect the reliability of measurements during the tests.

For this reason, this work presents the development of a fiber optic-based insole for estimating gait sub-phases. However, it is proposed to use the activation of the different sensor points (no force is used, only the raw values). To determine which point corresponds to which phase, the results of the insole will be compared with the results of a force platform, and thus determine their relationship between the two signals.

2. OBJECTIVES

2.1. General Objective

Estimate the gait phases using a fiber optic-based insole during different walking gait.

2.2. Specifics Objectives

- Design and implement a 3D-printed fiber optic-based insole.
- Propose an experimental protocol to evaluate the proposed sensor with healthy subjects in a motion analysis laboratory with force platforms.
- Evaluate the fiber optic-based insole during gait subphases estimation through force platforms.

3. MATERIALS AND METHODS

This section describes the fiber optic-based sensor that was implemented to execute the study. Moreover, it describes the experimental protocol that was carried out to validate the detection of gait sub-phases with the proposed insole.

3.1. Fiber Optic-based Insole Description

This work used the fiber-optic insole presented in Figure 1. This sensor structure was 3D-printed using the Guider IIs (Flashforge 3D Technology, Chinese) with thermoplastic polyurethane (elastic and flexible printing material, frequently referred to as TPU). According to [31], the layer height and material infill density were set to 0.2 mm and 80%, respectively.

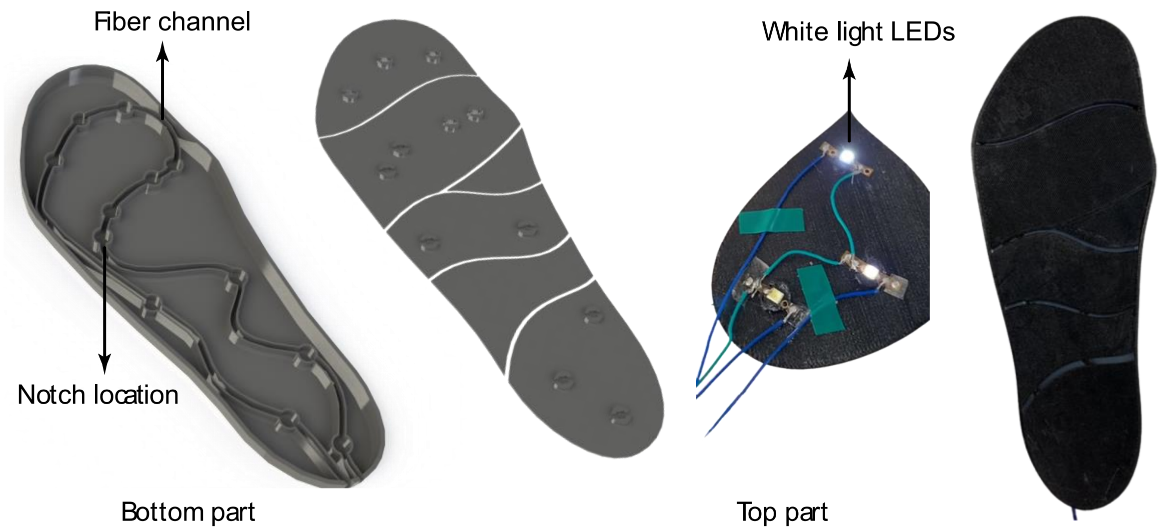

Figure 1. Proposed fiber-optic-based insole for data acquisition.

As can be observed, the insole was divided into two sections: (1) Bottom part and (2) Top part. The base part is mainly flexible, allowing deformation on contact that provides comfort during walking. Besides, this contains the PMMA POF (HFBR-EUS100Z, Broadcom Limited) with its respective notches, where the filament is weakened for the light input. This fiber optic has a numerical aperture of 0.47, a layer of fluorinated polymer with 10 µm thickness and a PMMA core with 980 µm diameter.

On the other hand, the upper cover is divided into four sections (i.e., hell zone, midfoot zone, metatarsal zone and toe zone) to avoid interference at other sensing points where the force is applied. LEDs were attached to each segment in a manner that the emitted light is aimed at the notches in the fiber. The light sources used were LEDs (ASMT-BR20-AS000 Broadcom Limited) with a center wavelength set for white light and a luminous intensity of 650 mcd.

Finally, for the measurement of the change in the power of light the photodetectors employed were photodiodes IF-D91 (Industrial Fiber Optics, USA). For this specific case, the inverter configuration indicated in the datasheet was implemented. For this reason, the activation of the pressure point is seen when the signal is decreasing. The signal acquisition and the LED control were performed by the microcontroller FRDM-KL25Z board (Freescale, Austin, TX, USA).

3.2. Experimental Protocol

3.2.1. Session Environment

This study took place at the Motion Analysis Laboratory (MAL) of the EPF School of Engineering in France.

3.2.2. Participant Recruitment

Table 1 summarizes the demographic data of the subjects who were formally recruited to participate in the validation study.

Subject	Gender	Age	Weight (Kg)	Height (m)	Shoe Size (EU)
1	Male	21	60	1.79	41.5
2	Female	21	68	1.73	42.5

Table 1. Demographic information of the participants involved in the study.

- **Inclusion Criteria:** Healthy adults between 18 and 50 years of age who were in optimal condition to perform walking tasks.

- **Exclusion Criteria:** Subjects with pathologies associated with alterations in normal gait parameters were excluded from the study.

3.2.3. Experimental Procedure

Before starting the tests, participants had to fill out an informed consent form to ensure that they had voluntarily expressed their intention to participate in the research. Participants only had to attend one session (i.e., a total of 2 sessions were conducted).

Then, after a free warm-up of at least 5 min, each participant was asked to perform a task: walk at comfort speed. This task was carried out on force platforms (AMTI, Watertown, MA) sampled at 1 kHz, located in the center of the 15-meter-long motion analysis room. For walking, it was requested to impact at least one different platform with the right and left foot. In all cases, participants were encouraged to keep their gaze straight ahead so as not to disturb the movement.

In addition, a familiarization period was provided to help participants with the experimental context before the measurement sessions. For each task, participants executed as many trials as necessary to collect ten successful trials, based on the task completion criterion (movement without visual disturbance and successful force measurement). Finally, it is important to highlight that considering the distribution of the force platforms, four steps were recorded for each participant, i.e., two steps for each foot.

3.2.4. Data Processing and Analysis

Data processing was mainly performed in MATLAB. The signals estimated from the fiber optic sensor were directly compared with the force platform measurements for the different tasks performed, based mainly on the statistical analysis (according means or estimated errors). Furthermore, the relationship between these signals was estimated, i.e., it was tried to find what was the representation of each of the insole signals within the platform force signal.

3.2.5. Ethics Statement

The Research Ethics Committee of the EPF School of Engineering approved this experimental protocol. The participants were informed about the experiment's scope and purpose, and their written informed consent was obtained before the study. The participants were free to leave the study when they decided to do so.

4. RESULTS

Figures 2 and 3 report the signals from the force platforms and the insole. The left column shows the results obtained from the first step and the right column shows the results obtained from the second step. The solid line represents the mean while the faded part represents the standard deviation of subject's tests.

Furthermore, Figure 2 shows the results obtained from the tests performed by the first subject.

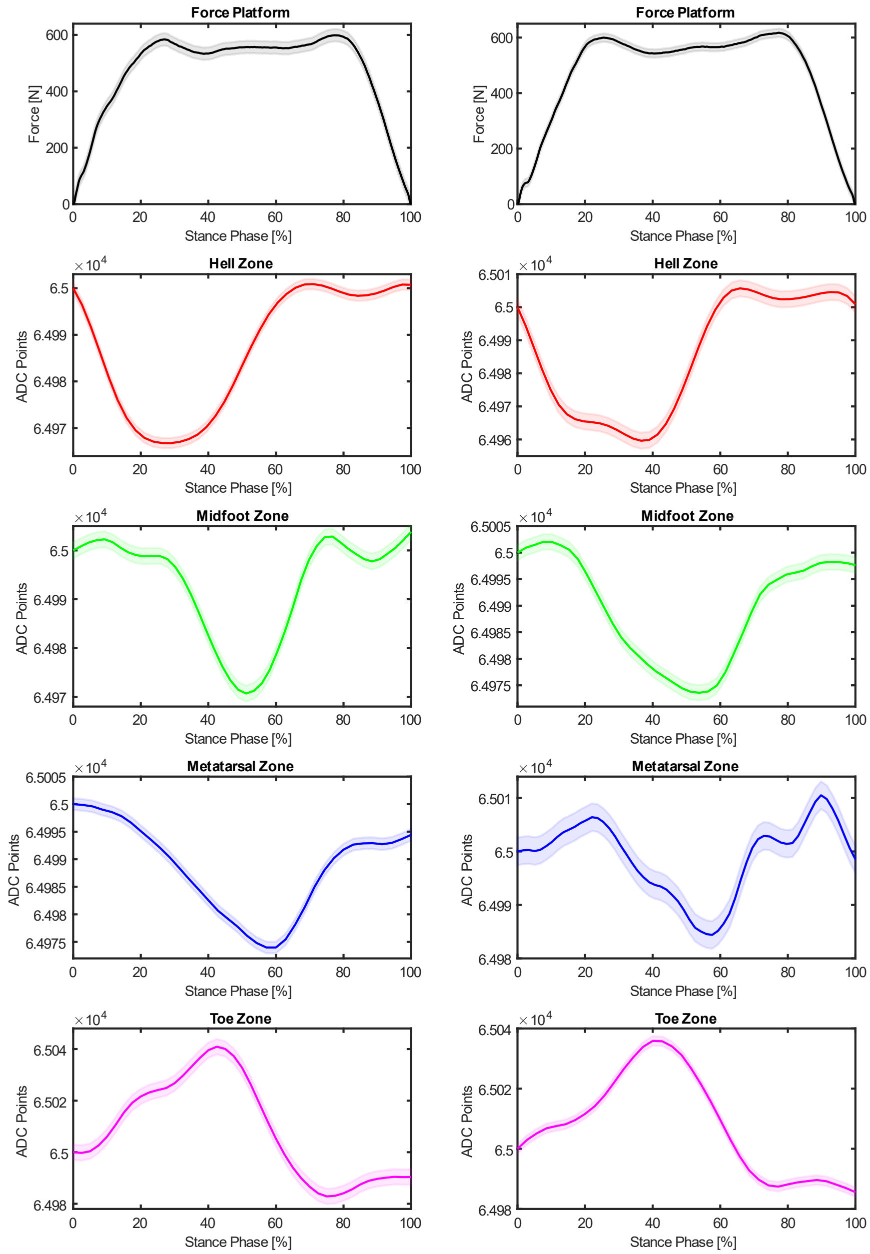

Figure 2. Results obtained from the first participant. The graphics on the left represent the first step. While those on the right are of the second step.

Figure 3 shows the results achieved from the tests conducted by the second participant.

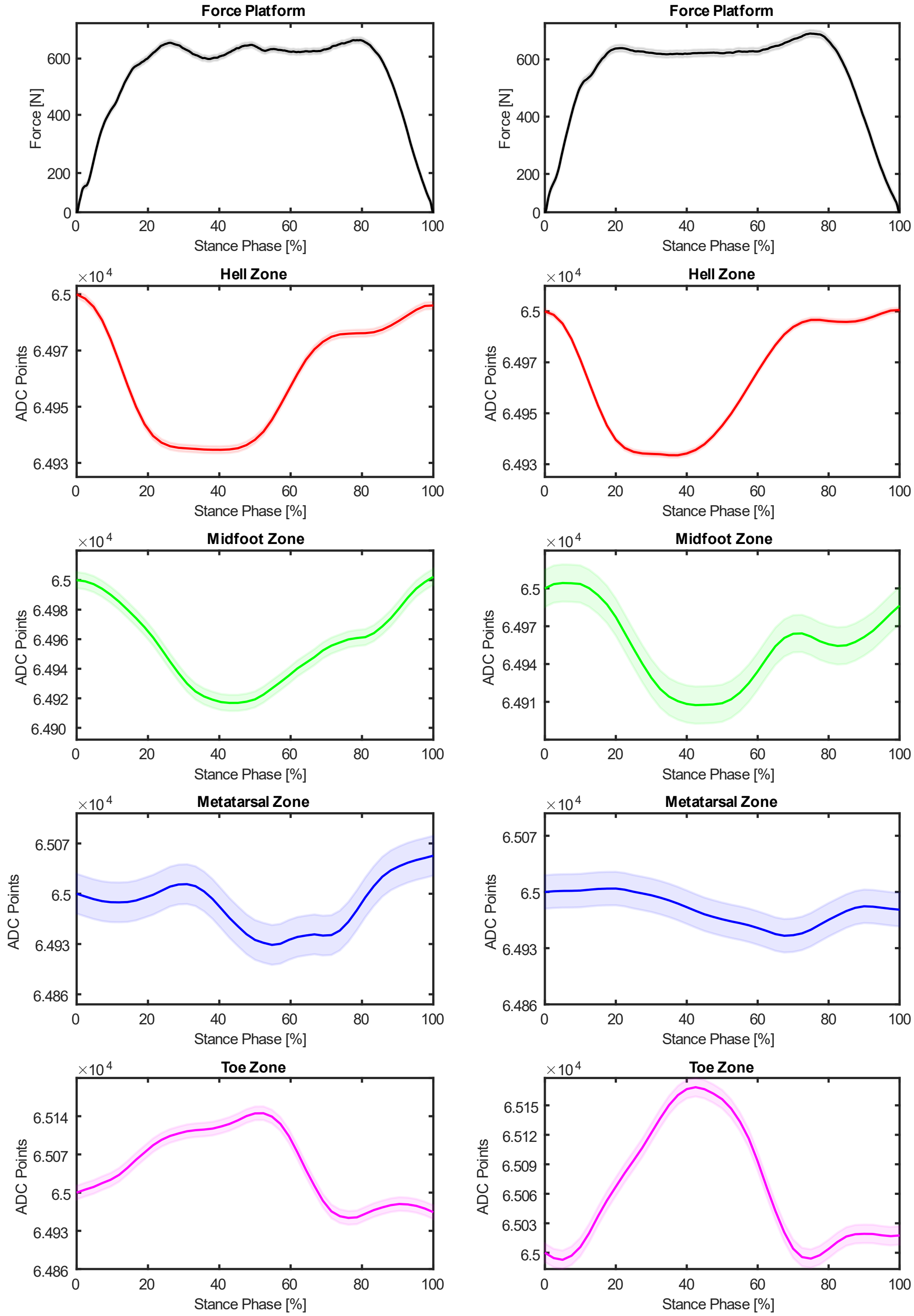

Figure 3. Results reached from the second participant. The graphics on the left represent the first step. While those on the right are of the second step.

Regarding the insole signals and according to the behavior of each pressure point, it was decided to report the one with the best performance (in terms of sensitivity) of each of the 4 zones. To compare the behavior of each of these with the signal from the force platform, the four points were cut from the first contact of the heel area to the last contact of the toe area.

This latter, allowed comparison of whether the activation of each point on the insole matched any of the subphases of gait that could be detected in the force platform signal (i.e., flat foot (FF) when the foot is parallel to the ground, heel off (HO) phase and toe off (TO), where the former is when the heel loses contact with the ground and the latter is in the vicinity of the swing phase when the toe is not in contact with the ground. In this analysis, also were considered a maximum weight acceptance (MA) phase when there is a local peak of the GRF, which resulted in the well-defined M shape of the GRF during the gait [31]).

Considering this, for the case of both subjects the MA sub-phase, relates to the behavior of the insole when the heel area is fully activated. For the FF sub-phase, the midfoot zone and the metatarsal zone are activated. Finally, the activation of the toe zone is consistent with the HO sub-phase.

5. DISCUSSION

A preliminary evaluation of a low-cost fiber optic-based insole was reported, in which a novel multiplexing technique for this type of technology was implemented [32]. This method made it possible to abrade a lateral section of the fiber to increase its sensitivity to variations in force and pressure. Moreover, it allowed the configuration of the intensity of each of the sensors to avoid saturation of each notch.

By achieving this, it was possible to multiplex several sensors on the same fiber optic strip and therefore only two phototransistors were needed. This resulted in a system with capabilities similar to the fiber Bragg gratings (FBG) but given the requirement for high-priced interrogation equipment and specialized lasers for FBG sensor manufacture, the cost of these fiber optic sensors is considerably lower [33].

On the other hand, the insole was manufactured with flexible plastics such as TPU using a 3D printer. The ease of manufacturing, the relatively low cost, the possibility of customization and large-scale manufacturing are some of the advantages that this construction process offers. In addition, this methodology facilitates the optimization of the number and positioning of the sensors for each user, considering the anatomy of the foot.

Regarding the study and validation of the measurements provided by the insole, for the case of subject 1 (see Figure 1) according to the graphs of the force platform, the MA phase occurs at approximately 22% of the stance phase (in both steps), however, in the insole signals (i.e. Hell Zone) for step 1 this occurs at 26% and for step 2 at 27% of the stance phase, this indicates an error of 18.18% and 22.72%, respectively. On the contrary, for subject 2, the MA phase occurs at approximately 32% of the stance phase of both steps, talking about the insole data. This indicates that the estimation error of this phase for subject 2 presents a greater error concerning the values of the force platform, however, this may be related to the fact that the insole that was evaluated has a size of 41.5 EU, and the size of the foot of subject 2 is 42.5 EU. This difference could significantly affect the measurements for this specific phase.

In the case of the FF phase, it can be seen in Figures 1 and 2 that the midfoot and metatarsal zones are related. The insole signals are between 40% and 60% of the stance phase, which is where the flat foot sub-phase occurs (see the force platform signals). However, it is important to note that the standard deviation for these zones increases reasonably, this is related to the fact that this sub-phase is affected by the gait speed of each participant [31].

Finally, the HO sub-phase presents the best results, as the insole data from both subjects indicates that the Toe Zone was activated between 76% and 79% of the stance phase. Considering the results of the force platform (HO was present at 79% of the stance phase) the estimation error of this gait phase did not exceed 4%. These results may be related to the sensitivity of the sensors in that area, since due to their location, from a single point it was possible to read light intensity from the two phototransistors.

6. RECOMMENDATIONS AND FUTURE WORK

This work presented the development of a fiber optic-based insole and its respective evaluation with two subjects for the detection of gait subphases. However, there are several points where the sensor design and experimental protocol can be improved.

One of them is the height of the insole, since the one implemented in this study was 1 cm. This is related to the ergonomics and comfort of the participant during the tests. Caution should be exercised in achieving this, as reducing the height too much can considerably affect the range of each of the pressure points.

For the manufacture of the insole, more processes should be explored to improve the replicability and make it easier to build. For this case, different insoles had to be produced to achieve consistent measurements at each of the pressure points.

Furthermore, a strategy can be proposed to calibrate the insole to estimate force with it. This can make easier the comparison between the signals from the force platform and the results obtained by the sensor.

For future work, it is necessary to develop more insoles of different sizes, in order to recruit more participants regardless of their foot size. This may allow the study to be more robust and an interesting statistical analysis could be performed.

On the other hand, as for the experimental protocol, more complex gait tests can be proposed (e.g., including turns or obstacle avoidance) and even tasks such as running and jumping can be proposed.

7. CONCLUSIONS

This report presented the development of a fiber-optic-based insole for estimation of gait subphases. It was proposed to manufacture it in 3D printing material, to be a great alternative to commercial sensors that often have very high prices. Furthermore, a novel technique was implemented that allowed to have several sensors on the same fiber strip, which can be valuable to increase or decrease the number of pressure points and thus improve the response of the insole and offer the possibility to customize it for each subject.

This sensor was evaluated with 2 healthy subjects, which allowed the first results of the proposed strategy to be obtained. Although the results were positive, it is important to highlight that the number of samples to be evaluated should be increased in order to have better indicators when comparing the results with force platforms or other commercial sensors. Besides, more complex tasks can be included to evaluate other aspects of this type of insoles.

The proposed insole can identify 3 sub-phases of gait, such as maximum weight acceptance, flat foot and heel off, which are of extreme importance for the diagnosis of pathologies and are widely used for the control of robotic devices for gait assistance and rehabilitation. However, other strategies that allow the identification of other gait phases such as Heel strike and Toe off, which are well-studied in the literature, should be studied in more detail.

Finally, regarding the results obtained from the estimation of the gait phases by the insole, the Heel Off gait sub-phase obtained excellent results since the error for both subjects did not exceed 4%. This was obtained mainly due to the position of the zone and the fact that the phototransistors could read more light power from these points. For this reason, strategies should be implemented to considerably increase the light intensity of the other zones, so that their sensitivity improves, and more accurate results can be obtained.

REFERENCES

[1] G. Cicirelli, D. Impedovo, V. Dentamaro, R. Marani, G. Pirlo, and T. R. D'Orazio, "Human gait analysis in neurodegenerative diseases: a review," IEEE Journal of Biomedical and Health Informatics, vol. 26, no. 1, pp. 229–242, 2021.

[2] C. L. Vaughan, "Theories of bipedal walking: an odyssey," Journal of biomechanics, vol. 36, no. 4, pp. 513–523, 2003.

[3] C. A. Cifuentes and A. Frizera, "Human-Robot Interaction Strategies for Walker-Assisted Locomotion", Springer Tracts in Advanced Robotics. Cham: Springer International Publishing, 2016, vol. 115. Available: http://link.springer.com/10.1007/978-3-319-34063-0.

[4] S. D. Sierra M, D. E. Garcia A, S. Otálora, M. C. Arias-Castro, A. Gómez-Rodas, M. Munera, and C. A. Cifuentes, "Assessment of a robotic walker in older adults with Parkinson's disease in daily living activities," Frontiers in neurorobotics, vol. 15, p. 742281, 2021.

[5] W. H. Organization, Neurological disorders: public health challenges. World Health Organization, 2006.

[6] W. H. Organization, World report on ageing and health. World Health Organization, 2015.

[7] C. A. Cifuentes and M. Múnera, Interfacing humans and robots for gait assistance and rehabilitation. Springer, 2022.

[8] A. Kian, G. Widanapathirana, A. M. Joseph, D. T. Lai, and R. Begg, "Application of wearable sensors in actuation and control of powered ankle exoskeletons: A comprehensive review," Sensors, vol. 22, no. 6, p. 2244, 2022.

[9] D. Shi, W. Zhang, W. Zhang, and X. Ding, "A review on lower limb rehabilitation exoskeleton robots," Chinese Journal of Mechanical Engineering, vol. 32, no. 1, pp. 1–11, 2019.

[10] Y. Sun, Y. Tang, J. Zheng, D. Dong, X. Chen, and L. Bai, "From sensing to control of Lower Limb Exoskeleton: A systematic review," Annual Reviews in Control, vol. 53, pp. 83–96, 2022.

[11] M. D. Sánchez Manchola, M. J. Pinto Bernal, M. Múnera, and C. A. Cifuentes, "Gait phase detection for lower-limb exoskeletons using foot motion data from a single inertial measurement unit in Hemiparetic individuals," Sensors, vol. 19, no. 13, p. 2988, 2019.

[12] A. Miller, "Gait event detection using a multilayer neural network," Gait & Posture, vol. 29, no. 4, pp. 542–545, 2009.

[13] F. Attal, Y. Amirat, A. Chibani, and S. Mohammed, "Automatic recognition of gait phases using a multiple regression hidden Markov model," IEEE/ASME Transactions on Mechatronics, pp. 1–1, 2018.

[14] Y. Qi, C. B. Soh, E. Gunawan, K.-S. Low, and R. Thomas, “Assessment of foot trajectory for human gait phase detection using wireless ultrasonic sensor network,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 24, no. 1, pp. 88–97, 2016.

[15] N. Nazmi, M. A. Abdul Rahman, S.-I. Yamamoto, and S. A. Ahmad, “Walking gait event detection based on electromyography signals using artificial neural network,” Biomedical Signal Processing and Control, vol. 47, pp. 334–343, 2019.

[16] L. Yu, J. Zheng, Y. Wang, Z. Song, and E. Zhan, “Adaptive method for real-time gait phase detection based on ground contact forces,” Gait & Posture, vol. 41, no. 1, pp. 269–275, 2015.

[17] I. González, J. Fontecha, R. Hervás, and J. Bravo, “An ambulatory system for gait monitoring based on wireless sensorized insoles,” Sensors, vol. 15, no. 7, pp. 16589–16613, 2015.

[18] M. Islam and E. T. Hsiao-Wecksler, “Detection of gait modes using an artificial neural network during walking with a powered ankle-foot orthosis,” Journal of Biophysics, vol. 2016, pp. 1–9, 2016.

[19] M. Yuwono, S. W. Su, Y. Guo, B. D. Moulton, and H. T. Nguyen, “Unsupervised nonparametric method for gait analysis using a waist-worn inertial sensor,” Applied Soft Computing, vol. 14, pp. 72–80, 2014.

[20] M. Goršič, R. Kamnik, L. Ambrožič, N. Vitiello, D. Lefeber, G. Pasquini, and M. Munih, “Online phase detection using wearable sensors for walking with a robotic prosthesis,” Sensors, vol. 14, no. 2, pp. 2776–2794, 2014.

[21] X. Jiang, K. Chu, M. Khoshnam, and C. Menon, “A wearable gait phase detection system based on force myography techniques,” Sensors, vol. 18, no. 4, p. 1279, 2018.

[22] A. Behboodi, H. Wright, N. Zahradka, and S. C. Lee, “Seven phases of gait detected in real-time using shank attached gyroscopes,” 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015.

[23] M. Kim and D. Lee, “Development of an IMU-based foot-ground contact detection (FGCD) algorithm,” Ergonomics, vol. 60, no. 3, pp. 384–403, 2016.

[24] D.-H. Lim, W.-S. Kim, H.-J. Kim, and C.-S. Han, “Development of real-time gait phase detection system for a lower extremity exoskeleton robot,” International Journal of Precision Engineering and Manufacturing, vol. 18, no. 5, pp. 681–687, 2017.

[25] B. T. Smith, D. J. Coiro, R. Finson, R. R. Betz, and J. McCarthy, “Evaluation of force-sensing resistors for gait event detection to trigger electrical stimulation to improve walking in the child with cerebral palsy,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 10, no. 1, pp. 22–29, 2002.

[26] A. H. Abdul Razak, A. Zayegh, R. K. Begg, and Y. Wahab, “Foot plantar pressure measurement system: A review,” Sensors, vol. 12, no. 7, pp. 9884–9912, 2012.

[27] J. Castrellon-Uribe, Optical fiber sensors: an overview. IntechOpen, 2012.

[28] S. Subramaniam, S. Majumder, A. I. Faisal, and M. J. Deen, “Insole-based systems for health monitoring: Current solutions and research challenges,” Sensors, vol. 22, no. 2, p. 438, 2022.

[29] M. F. Domingues, C. Tavares, C. Leitao, A. Neto, N. Alberto, C. Marques, A. Radwan, J. Rodriguez, O. Postolache, E. Rocon et al., “Insole optical fiber bragg grating sensors network for dynamic vertical force monitoring,” Journal of biomedical optics, vol. 22, no. 9, p. 091507, 2017.

[30] R. A. Lakho, Z. Yi-Fan, J. Jin-Hua, H. Cheng-Yu, and Z. Ahmed Abro, “A smart insole for monitoring plantar pressure based on the fiber bragg grating sensing technique,” Textile Research Journal, vol. 89, no. 17, pp. 3433–3446, 2019.

[31] A. G. Leal-Junior, C. R. Díaz, C. Marques, M. J. Pontes, and A. Frizera, “3D-printed POF insole: Development and applications of a low-cost, highly customizable device for plantar pressure and ground reaction forces monitoring,” Optics & Laser Technology, vol. 116, pp. 256–264, 2019.

[32] A. G. Leal-Junior, C. R. Díaz, C. Marques, M. J. Pontes, and A. Frizera, “Multiplexing technique for quasi-distributed sensors arrays in polymer optical fiber intensity variation-based sensors,” Optics & Laser Technology, vol. 111, pp. 81–88, 2019.

[33] D. Vilarinho, A. Theodosiou, C. Leitão, A. Leal-Junior, M. Domingues, K. Kalli, P. André, P. Antunes, and C. Marques, “POFBG-embedded cork insole for Plantar Pressure Monitoring,” Sensors, vol. 17, no. 12, p. 2924, 2017.