Article

Insole Gait Acquisition System Based on Wearable Sensors

Niharika Gogoi*, Zixuan Yu, Yichun Qin, Jens Kirchner and Georg Fischer

[1] Institute for Electronics Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058, Erlangen, Germany

* Correspondence: niharika.gogoi@fau.de

Abstract: Human gait analysis is a growing field of research interest in medical treatment, sports training and structural health monitoring. In our study, we propose a low cost insole design with wearable sensors based on piezoelectric discs (PZT) and inertial measurement unit (IMU) to acquire the human gait. The sensors are placed at three points of a shoe sole: toe, metatarsal and heel. The human gait obtained from such an insole layout is significantly affected by plantar pressure distribution and alignment of the feet. The PZT sensors give an insight about pressure map under the feet and the IMUs record projection and orientation of the feet.

Keywords: gait; piezo; IMU; plantar pressure

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Journal Not Specified* **2021**, *1*, 0. https://doi.org/

Received:
Accepted:
Published:

1. Introduction

Human gait analysis is the study of graphical representation of human motion to understand the condition of human muscles, mechanics and fitness. It helps in prevention, treatment and diagnosis of many diseases, sports training and improvement of postures [1]. The neurological and musculoskeletal illnesses such as aging, Parkinson, thrombosis, stroke and diabetes affect the stride characteristics and human gait quality at the same time: They lead to a decrease in stride length, shuffling steps, fall risk or impaired gait initiation [2–6]. There are primarily two methods of gait analysis: video and image processing based, and sensors based. Video/Image processing system capture 3D data of the subject's gait through one or more highly accurate optic sensors and use digital image processing to study the recorded visual measurements of the different parameters [2]. In most motion laboratories, this technique is used for complete analysis of the motion of all body segments. Sensor based techniques, on the other side, are of two types: non wearable and wearable sensors. The non wearable systems refer to sensor arrangements at a specific location such as floor mats or treadmills. The wearable systems refer to sensors placed on several parts of human body like thighs, feet, ankle, etc, which can monitor movements without restricting to a fixed location or fixed duration of monitoring; out of which, IMU is the most commonly used wearable sensor for gait monitoring [1,7,8].

In relevance to gait study, our area of focus lies in gait acquisition from wearable sensors placed on shoes. Since foot wear is an important part of our daily lives, it provides an important means to assess gait characteristics for not only sick and old but also for athletics trainings and daily gait monitoring [9–11]. The long-term monitoring of gait is an advantage of in-sole sensors compared to video/image processing systems. Shu et al. and Chen et al. used their own customised array of pressure sensors, Moris et al. used four different types of sensors and an IMU to acquire gait from the feet movement [6,12,13] and Zhao et al. placed an IMU on a shoe behind the ankle to acquire gait data [3]. However, behaviour of IMUs with pressure sensors under the feet is still not investigated for understanding foot movement.

In our study, we propose a shoe insole with sensor modules at three points under the feet: toe, metatarsal and heel. Each sensor module has an IMU integrated with a low-cost piezoelectric disc as pressure sensor, where the sensors are aligned in the same axis. With our proposed set-up, an array of such sensor modules is introduced, where at each measurement point and instant, plantar pressure as well as orientation, and linear and rotational acceleration of the feet are captured. This study promises a large amount of data collection from multiple low-cost sensors over a long real-time, specifically to portray foot motion. From our study of multiple IMUs, we expect to figure out the right location to place IMU inside the sole for gait applications. The multiple piezo sensors will provide an estimate of high pressure and low pressure points across the feet, which will be useful for both energy harvesting applications and gait analysis.

2. Sensors

2.1. Piezoelectric Sensors

Piezoelectricity is a property of certain dielectric materials: When a force or pressure is exerted on such a material, then the mechanical deformation generates charge on its surface, which is measured as voltage (direct piezoelectric effect) [14]. This characteristic is exhibited by many materials, including quartz crystals, semi-crystalline polyvinylidene polymer, polycrystalline piezo-ceramic, etc. In our project, we use Lead Zirconate Titanate i.e., PZT. It is widely used due to high dielectric values (K_3^T up to 3400 by PZT-5H and K_1^T up to 1700 by PZT-5A [14]) and reliability and stablility amongst all piezoceramics. Furthermore, PZT are physically strong, chemically inert, low-cost, light-weight and easy to implement.

2.2. IMU Sensors

Inertial measurement units include accelerometers, gyroscopes and even magnetometers. They are used to measure acceleration and orientation of an object. In most IMUs, there are three axes with gyroscopes, three axes with accelerometers and a computer for coordinate conversion to constitute an IMU for measuring the information of the carrier [1]. When placed on the feet for the purpose of gait analysis, the accelerometer gives the change of velocity of the feet [15]. The gyroscope gives the details of the orientation and posture of feet by measuring its angular rate [1,16], from which the angular velocity and angle of feet during the motion can be derived.

3. METHODOLOGY

3.1. Hardware Design

An aluminium structure was designed to be placed at the three positions inside the shoe sole. Fig. 1 shows its design with positions of the sensors. The diameter of inner sub-structure is 2.5 cm and the diameter of outer one is 3 cm. The whole set-up was constructed in such a way that it keeps the IMU on PCB and PZT discs together in the same axis. The IMU is placed inside the inner sub-structure and the piezo is placed in the outer one. Due to its metallic structure, it keeps the sensors safe without any possibility of cracks. The integrated aluminium structures are positioned at the mentioned three points in the left shoe (Fig. 2).

We use PZT discs from Murata Electronics. Its diameter is 12 mm and the resonance frequency is 9.0 kHz [17]. The BMI270 from Bosch is used as IMU [18]. In the shoe application, the PZT signal is related to plantar pressure distribution. The IMU signal in x direction defines the walking direction of the person, in y direction defines diversion of the feet either left or right from the straight path and in z direction defines the lifting of the feet from the ground. The gait signals of three people with different weights are measured with each person taking 10 steps. Table 1 gives details of the three subjects.

Table 1. Information about 3 Subjects

Physical Quantity	Subject 1	Subject 2	Subject 3
Age (Years)	26	27	27
Weight (Kg)	52	60	70

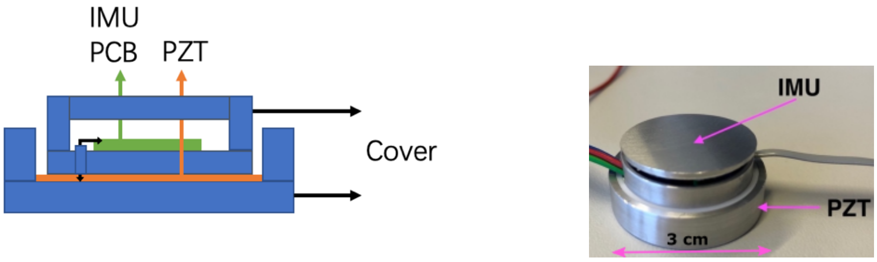

Figure 1. Structure design: schemantic (left) and final structure (right)

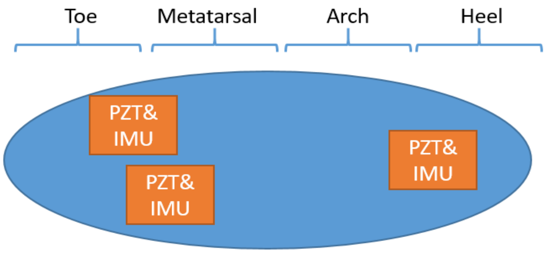

Figure 2. Sole layout

3.2. Data Acquisition

Fig. 3 (a) shows the block diagram for data acquisition connection from the sensors to SD card. The ADC module ADS115 is used to obtain the accurate piezo data using analog port and multiplexer TCA9548A to acquire data from all the IMUs (Fig. 3 (a)). I2C interface is used between multiplexer and the microcontroller Arduino Due (A-Due), and between ADC and A-Due. For data storage, an SD card is connected to A-Due through SPI interface. A-Due does two tasks at the same time. Firstly, it will acquire data from the array of sensors and secondly, it will save the acquired data directly on the SD card to facilitate subsequent data analysis. It is to be noted that the simultaneous reading and storing of the accurate data of the multiple sensors limits the sampling rate. The electrical connection on the PCB with senosrs, multiplexers and ADC is shown in Fig. 3(b).

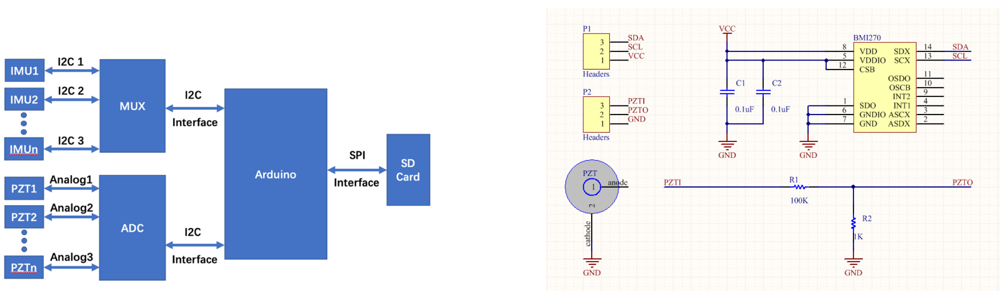

Figure 3. (a) Data acquisition connection (left) and (b) Electrical connections of the sensors inside the structure (right)

4. Results and Discussion

4.1. Gait Signal from Piezo Sensors

Fig. 4 shows gait measurements of 3 subjects. Each gait has roughly 5 stride regions, separated by dotted lines as guide to the eyes, depending on the pressure exerted and pronation while walking. The number of peaks generally imply the number of strikes with the ground but the peaks are not prominent at all points of the feet. It is to be noted that each individual has different walking frequency and different points of contact with the ground. In general, the walking pattern of an individual is expected to strike the ground in the order heel, arch, metatarsal and toe. It is observed that the subject 1 has no heel contact and mainly walks putting pressure on toe and metatarsal. Subjects 2 and 3 in contrast put pressure on their metatarsal points, where it is observed that subject 2 has more pressure points on metatarsal than on toe and heel. On the other hand, subject 3 puts more pressure at heel and metatarsal points while starting and ending the walk. The desired striking order as assumed (heel, arch, metatarsal and toe) and real gaits of individuals as shown in Fig. 4 tend to differ depending on plantar pressure distribution, which is affected by the body pressure on the feet as well as force used to strike the ground [15,16,19–22]. The gait pattern varies from time to time when the same person walks in the same pattern. It is shown in Fig. 5 that the number, frequency and magnitude of peaks are different for the same individual walking at two instances. This intra-individual variations are likely to occur in daily situations, which make the gait study not only interesting but also complicated to assess.

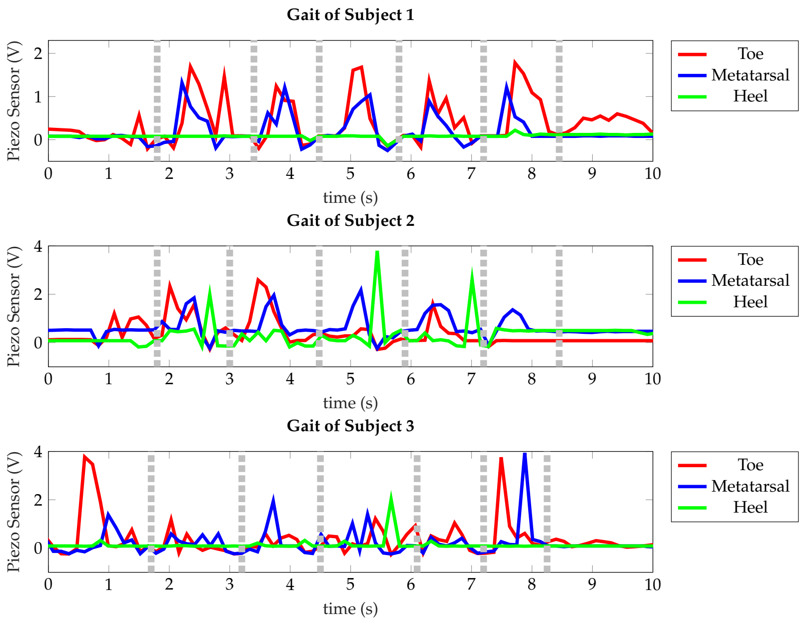

Figure 4. Gait of 3 people

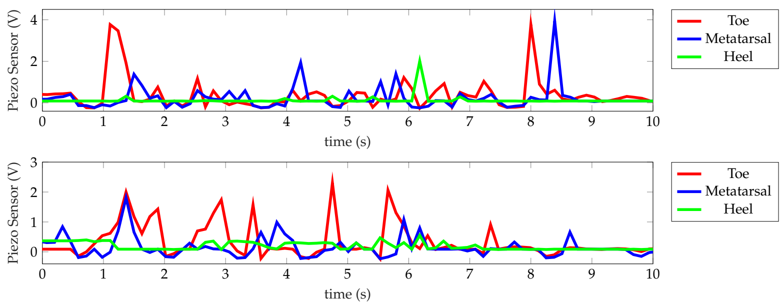

Figure 5. Gait of Subject 3 at different instances

4.2. Gait Signal from IMU Sensors

In Fig. 6, the IMU signals, obtained from accelerometer and gyroscope data, at the metatarsal are shown to relate with respect to the signal obtained from piezo sensor at the same position. The IMU data helped to identify the peaks occuring while striking with the ground, which are gray circled in the figure below. The linear and rotational acceleration graphs repeat after certain interval. Their amplitudes are inconsistent, which depends on the way with which the feet is lifted to strike the ground. As the feet takes the next step, the acceleration across x and z directions changes due to forward movement and lifting of the feet. The change of positions in these two directions are more prominent than that of y direction, which is obvious. For the gyro data, the angular changes are more distinct in x and y directions due to inward or outward landing variations of the feet and plantar rolling over the ground.

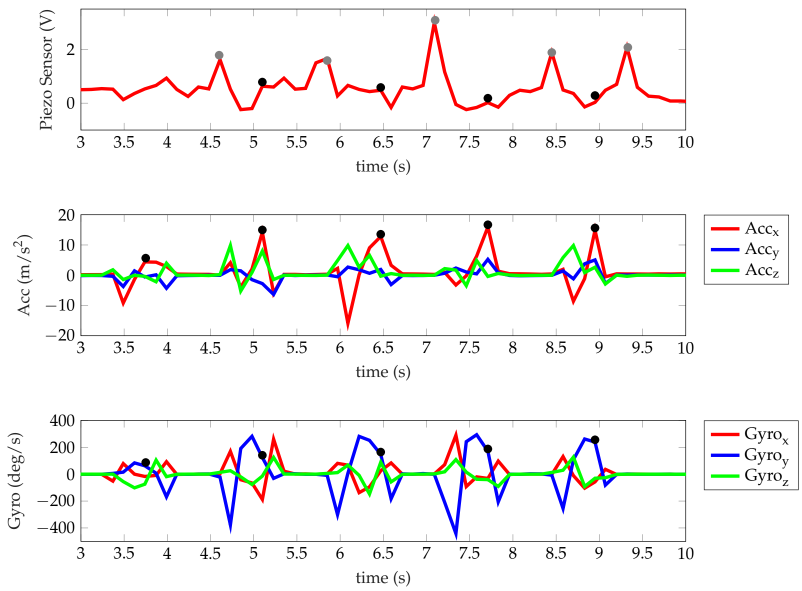

Figure 6. Signals at the metatarsal of Subject 2

5. Conclusions

In the proposed project, we have designed an insole structure with IMU and piezo sensors integrated together to obtain the gait of an individual at three points of the sole. The set-up collected pressure, linear acceleration and rotational acceleration of the left feet. We observe that metatarsal is the most impacted point of the feet, irrespective of the walking pattern of an individual. With increase in the number of such sensors, plantar map of high pressure points and low pressure points can be estimated. For 5 strides taken, IMU signals have 5 regions to identify each stride with corresponding peak in the piezo signal.

In future, we continue to increase the number of subjects and process the signals to correlate the behaviour of piezo sensors and IMUs. This shoe design is a promising idea to examine gait performance of a patient or an athlete or a health conscious individual with low-cost wearable sensors.

Author Contributions: Conceptualization: Niharika Gogoi, Methodology: Zixuan Yu, Yichun Qin, Writing: Niharika Gogoi, Review and Editing: Jens Kirchner, Supervision: Georg Fischer

Funding: The authors gratefully acknowledge financial support for this work by the Deutsche Forschungsgemeinschaft under GRK2495/A

Institutional Review Board Statement: Not Applicable

Informed Consent Statement: Not Applicable

Data Availability Statement: Not Applicable

Conflicts of Interest: The authors declare no conflict of interest

References

1. Tao, W.; Liu, T.; Zheng, R.; Feng, H. Gait analysis using wearable sensors. *Sensors* **2012**, *12*, 2255–2283. doi:10.3390/s120202255.
2. Ellis, T.; Cavanaugh, J.T.; Earhart, G.M.; Ford, M.P.; Foreman, K.B.; Dibble, L.E. Which measures of physical function and motor impairment best predict quality of life in ParkinsonâĂŹs disease? *Parkinsonism & Related Disorders* **2011**, *17*, 693–697. doi:10.1016/j.parkreldis.2011.07.004.
3. Zhao, H.; Wang, Z.; Qiu, S.; Shen, Y.; Wang, J. IMU-based gait analysis for rehabilitation assessment of patients with gait disorders. 2017 4th International Conference on Systems and Informatics (ICSAI). IEEE, 2017, pp. 622–626. doi:10.1109/ICSAI.2017.8248364.
4. Qiu, S.; Wang, Z.; Zhao, H.; Liu, L.; Jiang, Y. Using body-worn sensors for preliminary rehabilitation assessment in stroke victims with gait impairment. *IEEE Access* **2018**, *6*, 31249–31258. doi:10.1109/ACCESS.2018.2816816.
5. Sijobert, B.; Denys, J.; Coste, C.A.; Geny, C. IMU based detection of freezing of gait and festination in Parkinson's disease. 2014 IEEE 19th International Functional Electrical Stimulation Society Annual Conference (IFESS). IEEE, 2014, pp. 1–3. doi:10.1109/IFESS.2014.7036751.
6. Shu, L.; Hua, T.; Wang, Y.; Li, Q.; Feng, D.D.; Tao, X. In-shoe plantar pressure measurement and analysis system based on fabric pressure sensing array. *IEEE Transactions on information technology in biomedicine* **2010**, *14*, 767–775. doi:10.1109/TITB.2009.2038904.
7. Bamberg, S.J.M.; Benbasat, A.Y.; Scarborough, D.M.; Krebs, D.E.; Paradiso, J.A. Gait analysis using a shoe-integrated wireless sensor system. *IEEE transactions on information technology in biomedicine* **2008**, *12*, 413–423. doi:10.1109/TITB.2007.899493.
8. Muro-De-La-Herran, A.; Garcia-Zapirain, B.; Mendez-Zorrilla, A. Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications. *Sensors* **2014**, *14*, 3362–3394. doi:10.3390/s140203362.
9. Queen, R.M.; Haynes, B.B.; Hardaker, W.M.; Garrett Jr, W.E. Forefoot loading during 3 athletic tasks. *The American journal of sports medicine* **2007**, *35*, 630–636. doi:10.1177/0363546506295938.
10. Gioftsidou, A.; Malliou, P.; Pafis, G.; Beneka, A.; Godolias, G.; Maganaris, C.N. The effects of soccer training and timing of balance training on balance ability. *European journal of applied physiology* **2006**, *96*, 659–664. doi:10.1007/s00421-005-0123-3.
11. Chen, M.; Huang, B.; Xu, Y. Intelligent shoes for abnormal gait detection. 2008 IEEE International Conference on Robotics and Automation. IEEE, 2008, pp. 2019–2024. doi:10.1109/ROBOT.2008.4543503.
12. Morris, S.J.; Paradiso, J.A. Shoe-integrated sensor system for wireless gait analysis and real-time feedback. Proceedings of the Second Joint 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society][Engineering in Medicine and Biology. IEEE, 2002, Vol. 3, pp. 2468–2469. doi:10.1109/JSEN.2018.2832129.
13. Chen, D.; Cai, Y.; Huang, M.C. Customizable pressure sensor array: Design and evaluation. *IEEE Sensors Journal* **2018**, *18*, 6337–6344. doi:10.1109/JSEN.2018.2832129.
14. Covaci, C.; Gontean, A. Piezoelectric energy harvesting solutions: A review. *Sensors* **2020**, *20*, 3512. doi:10.3390/s20123512.
15. Zeng, H.; Zhao, Y. Sensing movement: Microsensors for body motion measurement. *Sensors* **2011**, *11*, 638–660. doi:10.3390/s110100638.
16. Catalfamo, P.; Ghoussayni, S.; Ewins, D. Gait event detection on level ground and incline walking using a rate gyroscope. *Sensors* **2010**, *10*, 5683–5702. doi:10.3390/s100605683.
17. Electronics, Murata. *7BB-12-9*. PD-SU2-C12-90.
18. Sensortec, Bosch. *BMI270*. Revision 1.3, doc.no. BSGT/BMI207/DS000-05, techn. ref. Code 0 273 017 008.
19. Park, J.S.; Lee, C.M.; Koo, S.M.; Kim, C.H. Gait phase detection using force sensing resistors. *IEEE Sensors Journal* **2020**, *20*, 6516–6523. doi:10.1109/JSEN.2020.2975790.
20. Hannink, J.; Kautz, T.; Pasluosta, C.F.; Gaßmann, K.G.; Klucken, J.; Eskofier, B.M. Sensor-based gait parameter extraction with deep convolutional neural networks. *IEEE journal of biomedical and health informatics* **2016**, *21*, 85–93. doi:10.1109/JBHI.2016.2636456.
21. Lin, F.; Wang, A.; Zhuang, Y.; Tomita, M.R.; Xu, W. Smart insole: A wearable sensor device for unobtrusive gait monitoring in daily life. *IEEE Transactions on Industrial Informatics* **2016**, *12*, 2281–2291. doi:10.1109/TII.2016.2585643.
22. Mueller, M.J. Application of plantar pressure assessment in footwear and insert design. *Journal of Orthopaedic & Sports Physical Therapy* **1999**, *29*, 747–755. doi:10.2519/jospt.1999.29.12.747.