Al-Nahrain Journal for Engineering Sciences **NJES** 25(4)152-158, 2022
http://doi.org/10.29194/NJES.25040152

Piezoelectric Fixing Direction effect on GRF test results in Wearable Shoe-Insole System

Ammar I. Kubba[1]

Authors affiliations:
1) Department of Prosthetics and Orthotics Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq.
ammar.i.salih@nahrainuniv.edu.iq

Paper History:

Received: 13th Oct. 2022

Revised: 24th Oct. 2022

Accepted: 19th Nov. 2022

Abstract

This article is about studying the placing direction effect of a piezoelectric sensor on the shoe insole in the GRF results. Where the sensors used in this research are in two directions, along and perpendicular to the foot midline. In the both cases the sensors were fixed on the shoe insole to sense the foot pressure. For the first set of sensors which are perpendicular to the foot midline the collected data has similar trend to the GRF collected from the force plate, as the small lateral strain in the shoe insole due to the patient weight and GRF is close to the GRF data collected from other measurement system. On the other hand, the collected data from the second set of sensors which are in a longitudinal direction with the foot midline will have different trend and values from the collected data from the force plate or any other GRF measurement system. This different in the results is due to the large longitudinal strain in the shoe insole due to the patient weight which produce dissimilar results from the force plate result data.

Keywords: Piezoelectric, Ground Reaction Force, Wearable System.

تاثير اتجاه حساس قياس قوة رد فعل الارض لخطوة المشي باستعمال نظام قياس مثبت في بطانة الحذاء

عمار عصام كبة

الخلاصة:

إن جمع بيانات قوة رد فعل الارض باستخدام نظام قياس ممكن ارتدائه واستعماله خلال الحياة اليومية خارج الظروف الخاصة بالمختبر يعد امرا ضروريا للحصول على بيانات قريبة من الواقع للاشخاص الذين يحتاجون متابعة بسسبب حالات مرضية او لاشخاص رياضين وذلك لتحسين ادائهم بصورة مستمرة. إن هذا البحث يدرس تاثير اتجاه وضع الحساس بحالتين الاولى بصورة طولية مع اتجاه محور القدم والثانية باتجاه عمودي على محور القدم. في كلا الحالتين فان الحساسات قد تم تثبيتها في بطانة الحذاء بنفس المواقع وبطريقة التثبيت. تم مقارنة النتائج المتحصلة من قراءات الحسسات مع نتائج القراءات المتحصلة من جهاز قياس قوة رد فعل الارض المختبري, وتبين ان القراءات من الحسسات المثبتة في الاتجاه العمودي على محور القدم تعطي نتائج قريبة من نتائج قراءات الجهاز المختبري وذلك بسبب ان الاستطالة الجانبية القليلة في بطانة الحذاء بسبب الوزن تكون نتائجها قريب من قوة رد فعل الارض. ولكن قراءات الحسسات المثبتة باتجاه محور القدم تكون قراءاتها غير مشابهة للنتائج المتحصلة من الجهاز المختبري بسبب ان الاستطالة الطولية الكبيرة في بطانة الحذاء نتيجة الوزن تعطي نتائج مختلفة عن قوة رد فعل الارض.

1. Introduction

Using a wearable measurements sensors system to collect the ground reaction force GRF data have been more reliable than using other methods [1]. These measurements were used to extract GRF data from range of human body daily activities [2]. Other technologies used to measure GRF such as F-scan, force plate or any other technologies are limited to

NJES is an **open access Journal** with **ISSN 2521-9154** and **eISSN 2521-9162**

laboratory conditions measurements only [3,4]. Several groups of researchers used GRF measurement as an indicator for the performance of the manufactured prosthetic or orthotics and to compare it to the sound lower limb [5, 6, 7]. During the last two decades, many researchers were studied the wearable GRF [8] as it become more reliable methodology to collect data for long time and wide range of daily activity. Also it can benefit patients who has problems in their feet e.g. diabetes or who have any other issues that needs monitoring [9]. There are many types of wearable sensor systems that can be used to collect the required data, based on the required aim of the study. In general, multiple local sensors system is the most widely used in this type of studies [8, 10, 11, 12, 13, 14, 15, 16, 17]. Other sensing technologies were using a full sensing pad for all the insole area to measure the GRF [18, 19, 20]. The full pad insole sensor (loadsol) which is a wireless single sensor pad sensor that measure the vertical ground reaction force [18]. The (loadsol) system and any similar system designed to measure the GRF cost much more than using a multi local sensors that located under the main pressure interface areas such as under heel, toe, metatarsophalangeal joint areas. In addition to any areas that might be important to examine the patient for a specific condition such as the area under the metatarsus arc to test the patient for flat foot condition. The multi-sensor measurement system can cost mush less than the full pad insole sensor and the cost is mainly based on the selected type of sensor. There are wide range of sensors that can be used for this application, accelerometers, pressure sensors, barometers, magnetometers, gyroscopes, [8]. Capacitance measurement system installed in the shoe insole was used to measure the GRF in several locations in under the foot during wide range of daily and athletic activities [9, 10, 11, 12], the capacitive sensors used in these researches measure the change in the capacitance value. This change is due to the movement of the distance between the capacitor plates when a pressure was applied. A resistance based sensor system was installed in the shoe insole to measure the GRF under the foot [13, 14], in these projects resistance based sensors were located in specific areas under the foot to measure the pressure. The interface pressure will lead to change in the dimension of the electrical resistance of the sensor material and a resistance measurement system was calibrated to measure the generated force. An optical sensor was developed to measure the GRF by assembling an optical source and sensor in opposite plates with spring between them to sense the applied pressure, this system can generate raw voltage data from the optical sensor that can be calibrated to pressure values [15, 16]. A micro-electro-mechanical system was developed to measure three axis GRF in the shoe insole [17], in this project a MEMS force measurement system was designed and fabricated to measure the GRF. The measurement was utilized by attaching the force sensor to rubber which located under the foot in 16 specific areas to collect the required GRF data.

Piezoelectric sensors also used by the researcher in earlier researches to measure the GRF in wide range of daily activities [21, 22]. Piezoelectric sensor produces voltage signal when any deformation was applied on them. These signals can be collected and calibrated to measure interface pressure, strain and other parameters. These measurements can be extracted from the generated signals based on the attaching conditions and the property of the material that attached to.

The aim of this article is to use piezoelectric sensors to measure the GRF. The piezoelectric sensors were located in specific areas where interface pressure can be detected. In this research the piezoelectric sensors were installed in two directions; along and perpendicular to the foot midline axis to find the more reliable sensor direction to present the GRF. The collected data were analysed then compared with the standard trend of the gait cycle GRF data.

2. Method

2.1. Subject

In this study one male participant accomplished the experimental part of the protocol, this participant has the following body properties; weight 80kg, height 178cm and 28 years old without any abnormality in his health, nervous system and musculoskeletal. The experiment protocol was clarified to the participant, then he did several attempts before collecting the data for this study.

2.2. The Wearable Measurement System

The wearable system which was used in this study is shown in figure 1 below and it has the following main parts: (LDT1-028K) piezoelectric sensor which its dimension is 25mm by 13mm [23]. These sensors were connected to an electronic circuit to filter the unwanted generated noise, the other part of this system is the (lab jack T7-PRO) data acquisition logger which transmitted the data wirelessly to a computer which can be saved and processed [24].

The piezoelectric sensor from (TE connectivity Ltd., Schaffhausen, Switzerland) serve multi-purpose such as, pressure sensor, strain sensor, and also it can work as vibration detector [23]. The piezoelectric sensor in this study work as pressure and strain sensor which these two sensors are attached to the shoe insole. The locations of the sensors were under the heel and metatarsophalangeal joint. The electronic band-filter circuit work as a filter for the unwanted signals which have frequencies far from the gait cycle. The electronic items for this band-pass filter are shown figure 2 below.

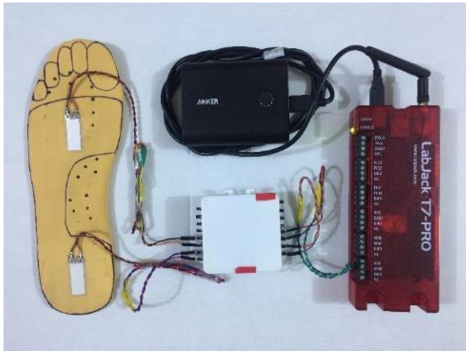


Figure (1): Wearable system parts
(a) Shoe Insole with two piezoelectric sensors, (b) Band pass filter electronic circuit, (c) Data acquisition logger, (d) portable charger

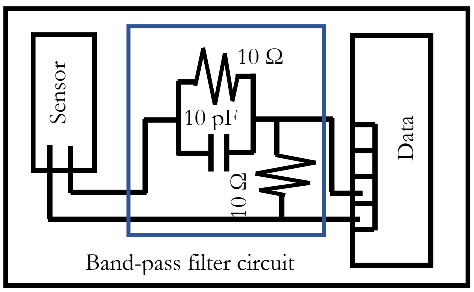


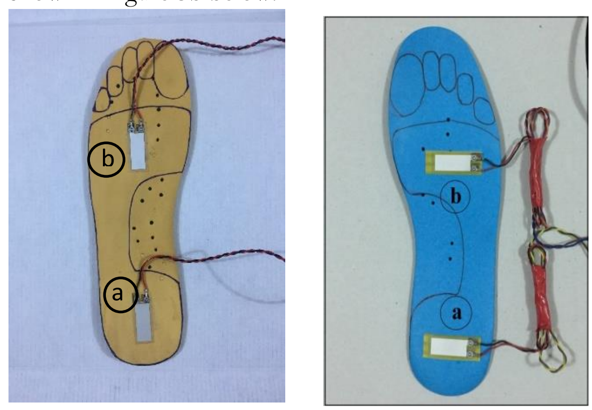
Figure (2): Band-pass filter electronic circuit [21,22].

The generated signal from the piezoelectric sensor was filtered through out the band pass filter electronic circuit then collected by the data logger to be transmitted through WiFi and saved in a PC computer. The data logger system is powered by portable charger (ANKER Power bank 13400, by Anker Technology) which can store 13400mAh charging capability. This charging capability were sufficient to run the experiment for several hours to accomplish the required data collection protocols. In the end the collected data were stored and processed in a PC computer after transmitting through WiFi connection, the data then analysed to extract the gait cycle measurement [21,22].

2.3. The Protocol

The experimental part for this study was delivered using two piezoelectric sensors were placed under the heel area and the other sensor was placed metatarsophalangeal joint area. The two positions were selected based on the main two locations where the GRF are transferred between the foot and the ground. The sensors location was selected through reviewing previous studies about the issue [9, 10, 14, 16] then by attempting several experiments to locate the spot where sufficient signal was generated from the piezoelectric sensors. For the heel area sensor, the location was selected after reviewing the related studies and attempting few experiments. On the other hand, locating the sensor which placed in the metatarsophalangeal joint area needed to attempt more experiments.

There are two major sets of data were delivered in this study, the first set when the piezoelectric sensors were placed in longitudinal direction with the foot midline axis, as shown in figure 3a below. And the second set when the piezoelectric sensors were placed in perpendicular direction with the foot midline axis, as shown in figure 3b below.



(a) **(b)**

Figure (3): Attached sensors to shoe insole a) in longitudinal direction to the foot midline axis, b) in perpendicular direction to the foot midline axis [21]

Several trials were attempt to finally locate the piezoelectric sensors then they attached to the shoe insole to run the experiments. After that the insole was placed into a sport shoe then the participant has put on the shoe and secured the rest of the measuring system items to his lower limb by a belt comfortably. The participant then starts to walk around for some time to achieve the required self-selected speed walking which was around 1.2 m/sec on the selected path for the experiment. The system then turned on, the WiFi connection with the PC was secured using a local router. And the data logger starts to transmit the collected data from the piezoelectric sensors. Several sampling rate was tested to find the suitable sampling rate value which can be used to find the gait cycle measurements. Then the data logger was set on 200Hz which was suitable for the walking speed and any other daily activity. Each experiment was utilized for at least 6 times to ensure that the average for these experiments after analysing was close to the real gait cycle for the participant.

2.4 Data collecting and processing

The generated signal from the piezoelectric sensors are collected as analogue voltage data in the (labjack) data logger. The data logger will transmit the collected data through WiFi connection to a PC where it can be stored and processed afterword. The collected voltage data represent the strain rate values at any time [25, 26]. The strain value can be found by numerally integrated the collected data with respect to time to find the strain value [21,22]. The founded strain values can be considered as interface pressure, shoe-insole strain, GRF or any other value using the required calibration and coefficients. Another factor that affect the type of the collected data, which is the attaching condition, the piezoelectric sensor will measure the shoe-insole strain if the sensor were glued and fixed to the insole.

The numerical integration was utilized by using General Trapezoidal Numerical Integration Formula, where its principle can be shown in the equation below:

$$\varepsilon=\int_{t=a}^{t=b} \dot{\varepsilon}\, dt \rightarrow F=\sum_{t=a}^{t=b} \left(\left(\dot{\varepsilon}(t) + \dot{\varepsilon}(t+1)\right)/2\right)\Delta t$$

Where: ε= strain, $\dot{\varepsilon}$= strain rate, a= the time of stepping beginning, b= the time when the strain required to be found, t= time and Δt= time interval [27].

The strain data found from this equation can be transformed to GRF data using the required coefficients that was found earlier. These coefficients were found by utilizing set of experiment using vibration kit consist of piezoelectric sensor attached to rubber and been excited shaker and the collected strain data was compared to accelerometer and load cell data [28, 29]. The extracted coefficients values will be used to find the values of the applied force from the measured strain values from the piezoelectric sensors.

3. Results

A sample of the collected raw voltage data from the piezoelectric is shown in the figure 4. As the data from sensor (a) from figure 3 represent the data (V1) in figure 4, and (F1) in figure 5, also the data from sensor (b) from figure 3 represent the data (V2) in figure 4, and (F2) in figure 5.

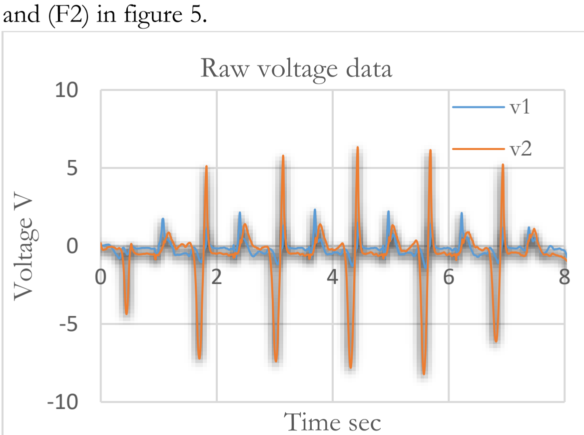
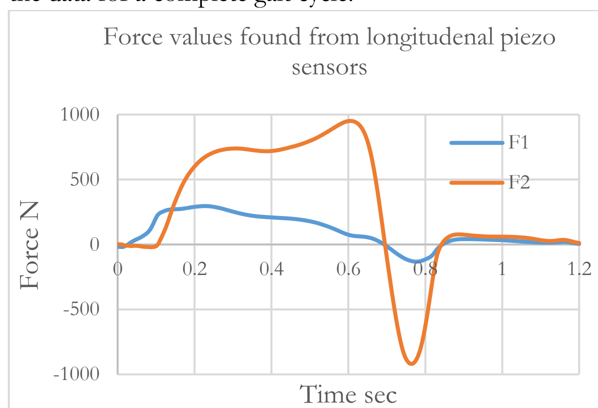
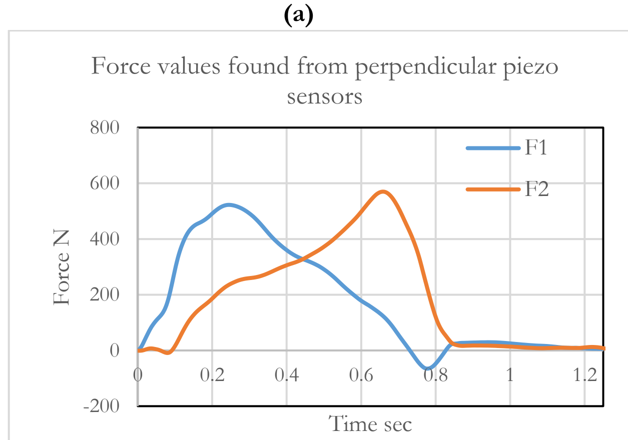


Figure (4): Strain rate signals raw voltage data for several steps.

The collected data above in figure 4 represent the piezoelectric sensor signal after being filtered and adjusted to the data logger requirements using the electronic circuit shown in figure 2. The data in figure 4, is extracted from the sensor which attached in the longitudinal direction to the foot midline. The above signal in figure 4, will be transformed to strain data using (General Trapezoidal Numerical Integration Formula) shown above. The calculated strain data then transferred to force using the coefficient cited above [28,29]. The force data are shown in figure 5 represent the calculated force values from the collected strain results from the piezo-sensor. These data shown in figure 5 are measured with piezo-sensor in longitudinal direction with the foot midline, and perpendicular with foot midline respectively. The data in figure 5 shows the data for a complete gait cycle.



(a)



(b)

Figure (5): Force calculated from the measured strain data using the piezo-sensor in a) longitudinal direction, b) perpendicular direction

Figure 5 shows a clear difference between the collected data from piezo-sensors in which installed in longitudinal and perpendicular direction to the foot midline. The difference in the measured data might be due to the difference in the shoe-insole strain. The insole longitudinal strain was probably generated due to the elongation happened during the gait cycle phases. As the foot heel starts contacting the ground, the backside of the foot and the shoe-insole will be fixed to the ground. The rest of the shoe-insole will start to stretch due to the friction force between the foot and the insole. This force will be very clear in the sensor which in longitudinal direction. And it would not be obvious in the sensor which was in perpendicular direction to the foot midline. On the other hand, the sensor in perpendicular direction to the foot midline senses the interface pressure clearly when compare its result to the data of same subject walking conditions at the force plate as shown in figure 6 [21,22]. The measured GRF with the force plate shows that the standard (M – shape) profile for the GRF, as the data from figure 6 represent the summation of the GRF from all the local sensors in the force plate under the foot print area. The calculated GRF (as shown in figure 5b) from the wearable measurement system used in this project by the two sensors in perpendicular direction is similar to the M-shape which measured by the force plate (as shown in figure 6). On the other hand, the collected data from the sensors which are in longitudinal direction with the foot midline (as shown in figure 5a) is different from the standard M-shape of the GRF (as shown in figure 6).

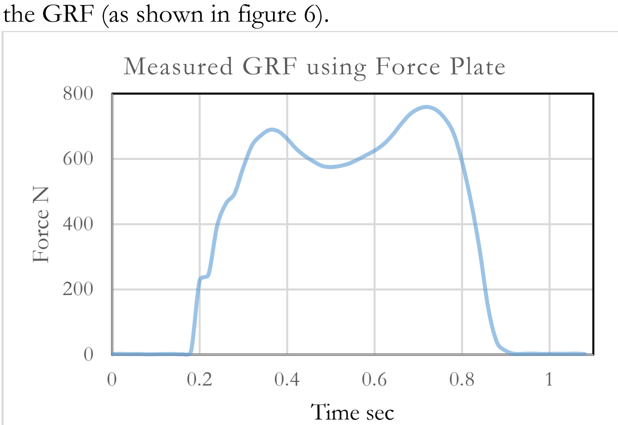


Figure (6): Measured GRF using force plate [21,22].

4. Discussion

The calculated force outcomes which measured from the strain data are affected with several measurement conditions, such as; the location where attaching the piezoelectric sensor, and the sensor attaching direction, which been investigated in this research. The collected data can present wide range of results based on the direction of installing the piezoelectric sensor. In this research two sets of experiments were utilized to find the generated signals in the piezoelectric sensor using wearable measurement system and find its physical explication.

The first set of data was utilized with sensors installed in longitudinal direction with the foot midline axis. From this experiment, the main value of the measured longitudinal data in the shoe insole represent the shoe-insole strain rather than the interface pressure. This strain was due to the longitudinal tension strain occurs in the shoe-insole during the gait cycle phases. It starts when the foot starts contacting the ground (heel strike phase) in the heel area as shown in figure 5a. The heel area will be as fixed support with the ground and shoe-insole will suffer from accumulated tension load due to the friction with the shoe and the foot. This tension load will increase with the gait cycle phase transform to mid stance and reaches its maximum value there. This behaviour can be shown in the sensor under the metatarsophalangeal joint area (sensor b shown in figure 3) which is F2 in figure 5a. then under the toe off phase of the gait cycle, the sensor signal will dramatically change towards compression due to the severe bending under the metatarsophalangeal joint area where the sensor will be on the top of the shoe bottom (shoe-sole) which suffer from compression stress. However, the other sensor located under the heel area (sensor a in figure 3) which its results shown in F1 will measure the GRF in the same trend as the sensor in perpendicular direction to the foot midline which shown in figure 5b, this similarity in the GRF trend shows less effect of the longitudinal load in the heel area might be because of the physical condition of fixing the shoe heel area between the ground and the foot.

On the other hand, the second set of results where the piezoelectric sensors are attached to the shoe insole in perpendicular direction to the foot midline as in figure 3b. The results shown in figure 5b, show close trend to the measured GRF using force plate. Also the measured value from the wearable sensor system installed in perpendicular direction to the foot midline shows similar GRF values to the measured GRF using force plate. This similarity in the result will make it very possible to use this system with this installation conditions as wearable GRF measurement system. Where this wearable system cost much less in compared with the force plate. Also, it can be used to measure the GRF in different daily activities in addition to athletics activities or as a monitoring system for any patients who need any measurements for any abnormal pressure on the foot such as diabetes.

5. Conclusions

The collecting (GRF) data using a wearable shoe insole system is very useful to improve the monitoring system. The suggested system cost is much less than the available ready to use products in the market. The (GRF) data could be for patient or the athletes who are in need to be observed in real life activity not only in laboratory conditions. This article was about studying the effect of the direction of piezoelectric sensors in the wearable shoe insole system, to find the direction which results the closest (GRF) data to the standard measured data from the force plate. It was found from this study that placing the piezoelectric sensors in a perpendicular direction to the foot midline will produce more close (GRF) data to the typical collected data from the force plate. The collected data from the second group where the sensors were placed along the foot midline are far from the typical collected data from the force plate data. The sensors locations, placing direction were studied in this article to find the closest data to the standard results from the force plate measuring system.

6. References

[1] Healy A, Burgess-Walker P, Naemi R, Chockalingam N. Repeatability of WalkinSense® in shoe pressure measurement system: A preliminary study. The Foot. 2012 Mar 1;22(1):35-9.
[2] Crea S, Donati M, De Rossi SM, Oddo CM, Vitiello N. A wireless flexible sensorized insole for gait analysis. Sensors. 2014 Jan;14(1):1073-93.
[3] Oerbekke MS, Stukstette MJ, Schütte K, de Bie RA, Pisters MF, Vanwanseele B. Concurrent validity and reliability of wireless instrumented insoles measuring postural balance and temporal gait parameters. Gait & posture. 2017 Jan 1;51:116-24.
[4] Catalfamo P, Moser D, Ghoussayni S, Ewins D. Detection of gait events using an F-Scan in-shoe pressure measurement system. Gait & posture. 2008 Oct 1;28(3):420-6.
[5] Hassan SS, Resan KK, Mahdi AZ. Design and Analysis of Knee Ankle Foot Orthosis (KAFO) for Paraplegia Person. Eng. & Tech. Journal. 2013 Jun 28;31(8).
[6] Kadhim FM, Ahmed SI. Stress Analysis of Thoracolumbosacral Orthosis (TLSO) for Scoliosis deformity and its Effects on Gait Cycle. Al-Nahrain Journal for Engineering Sciences. 2019 Oct 26;22(3):187-93.
[7] Jweeg MJ, Jaffar JS. Vibration Analysis of Prosthesis for the through knee Amputation. Al-Nahrain Journal for Engineering Sciences. 2016;19(1):46-55.
[8] Benson LC, Clermont CA, Bošnjak E, Ferber R. The use of wearable devices for walking and running gait analysis outside of the lab: A systematic review. Gait & posture. 2018 Jun 1;63:124-38.
[9] Motha L, Kim J, Kim WS. Instrumented rubber insole for plantar pressure sensing. Organic Electronics. 2015 Aug 1;23:82-6.
[10] Girard O, Eicher F, Micallef JP, Millet G. Plantar pressures in the tennis serve. Journal of Sports Sciences. 2010 Jun 1;28(8):873-80.
[11] Chuckpaiwong B, Nunley JA, Mall NA, Queen RM. The effect of foot type on in-shoe plantar pressure during walking and running. Gait & posture. 2008 Oct 1;28(3):405-11.
[12] Stöggl T, Martiner A. Validation of Moticon's OpenGo sensor insoles during gait, jumps, balance and cross-country skiing specific imitation movements. Journal of sports sciences. 2017 Jan 17;35(2):196-206.
[13] Tirosh O, Begg R, Passmore E, Knopp-Steinberg N. Wearable textile sensor sock for gait analysis. In2013 Seventh International Conference on Sensing Technology (ICST) 2013 Dec 3 (pp. 618-622). IEEE.
[14] Choi HS, Lee CH, Shim M, Han JI, Baek YS. Design of an artificial neural network algorithm for a low-cost insole sensor to estimate the Ground Reaction Force (GRF) and Calibrate the Center of Pressure (CoP). Sensors. 2018 Dec;18(12):4349.
[15] Park J, Na Y, Gu G, Kim J. Flexible insole ground reaction force measurement shoes for jumping and running. In2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob) 2016 Jun 26 (pp. 1062-1067). IEEE.
[16] Park J, Kim SJ, Na Y, Kim Y, Kim J. Development of a bendable outsole biaxial ground reaction force measurement system. Sensors. 2019 Jan;19(11):2641.
[17] Hori M, Nakai A, Shimoyama I. Three-axis ground reaction force distribution during straight walking. Sensors. 2017 Oct;17(10):2431.
[18] Renner KE, Williams DS, Queen RM. The reliability and validity of the Loadsol® under various walking and running conditions. Sensors. 2019 Jan;19(2):265.
[19] Randolph AL, Nelson M, Akkapeddi S, Levin A, Alexandrescu R. Reliability of measurements of pressures applied on the foot during walking by a computerized insole sensor system. Archives of physical medicine and rehabilitation. 2000 May 1;81(5):573-8.
[20] Burns GT, Deneweth Zendler J, Zernicke RF. Validation of a wireless shoe insole for ground reaction force measurement. Journal of sports sciences. 2019 May 19;37(10):1129-38.
[21] Kubba AI, Ameen AA. Gait Cycle Ground Reaction Force Measurement Using Piezoelectric Sensor Attached to Shoe-Insole System. InIOP Conference Series: Materials Science and Engineering 2020 Jul 1 (Vol. 881, No. 1, p. 012063). IOP Publishing.
[22] Kubba AI, Ameen AA, Al-Zuhairy RC. Measuring the Ground Reaction Force for Walking, Running and Stair Up/Down by Sensorized Insole System. Solid State Technology. 2020 Nov 1;63(3):3526-44.
[23] Measurement Specialties: LDT with Crimps Vibration Sensor/Switch. Measurement Specialties, Inc. (2008). https://media.digikey.com/pdf/Data%20Sheets/M

easurement%20Specialties%20PDFs/LDT0-028K.pdf .

[24] labJack T7-PRO, LabJack corporation, Colorado, USA, https://labjack.com/products/t7 , accessed on 10/12/2021

[25] Kubba, A. I.: Intelligent Tyre Technologies. University of Birmingham (2018).
https://etheses.bham.ac.uk/id/eprint/8363/

[26] Kubba, A. I.; Hall, G. J.; Varghese, S.; Olatunbosun, O. A.; Anthony, C. J. 2018: Modeling of Contact Patch in Dual-Chamber Pneumatic Tires. Tire Sci. and Tech. 46, 78-92.

[27] Kreyszig, E.: Advanced Engineering Mathematics 9th Edition with Wiley Plus WebCT Powerpack Set. John Wiley & Sons, Canada (2006).

[28] Kubba, A. I.: Intelligent Tyre Technologies. University of Birmingham (2018). https://etheses.bham.ac.uk/id/eprint/8363/

[29] Kubba, A.; Kubba, A.; Mahmoodi, N.; Olatunbosun, R.; Anthony C.: Experimental investigation on the dynamic response of piezoelectric transducer on tyre specimens. In the proceedings of the 37th Annual Meeting and Conference on Tire Science and Technology. Tire Society Inc. (2018).