Monitoring Diabetic Foot Ulceration Treatment with Smart Insoles and Neural Networks

Jeff van de Kamer[1], Maaike Hovenkamp[1], Erik Puik[1], and Diederik M. Roijers[1,2]

[1]Microsystems Technology, HU Univ. of Applied Sciences, Utrecht, the Netherlands
[2]AI Research Group, Vrije Universiteit Brussel, Brussels, Belgium
{jeff.vandekamer, maaike.hovenkamp}@student.hu.nl, erik.puik@hu.nl, diederik.roijers@vub.be

Diabetic foot ulceration is a painful and common complication of diabetes [3,9]. Because patients with diabetes lose sensitivity in their extremities, ulcers often develop relatively unnoticed for a longer period of time. Treatment of these ulcers often involves casting, which is expensive and intrusive. Removable devices for offloading pressure on the foot can help in this respect [1,4,6].

At HU University of Applied Sciences Utrecht, we have been developing 3D-printable insoles, that can be personalised to offload the pressure on the right locations of the foot. A further benefit of such personalised insoles is that they can be equipped with pressure (and other) sensors, which can be used to monitor the pressure on the foot as well as the treatment regimen. This regimen can involve that the patients keep up daily activities, such as walking and climbing stairs. Another key factor in successful treatment is compliance, i.e., the patient should wear the insole as much as possible. To assist in the treatment, we developed a prototype smart insole, which contains the aforementioned pressure sensors, as well as an accelerometer and a gyroscope to monitor both whether the insole is worn and the activities of the patients. As previous studies have indicated, providing feedback in this respect – both to the medical practitioners and the patients themselves [1] – can help improve the treatment of diabetic foot ulcerations.

To monitor compliance and activities, we need to be able to recognise whether the insole is being worn, and distinguish between the activities of the patient. This classification needs to be done continuously and locally in real-time. Because the insoles are a worn device, it is key that the energy usage of the device is as low as possible, as we cannot afford to charge the device often. Therefore, the entire process of data gathering, classification, and storing data is performed on a local micro-processing system. Specifically, our prototype runs on an Arduino Nano 33 BLE Sense [2]. The system is not multi-threaded, so the activity recognition needs to take significantly less time with respect to the time it takes to gather the data. Furthermore, the memory-capacity of the micro-processing system is limited. As such, in addition to sufficient *accuracy*, we require a classifier that is *fast*, *energy-efficient*, and *memory-efficient*.

The prototype consists of 3 main parts: (1) an Arduino Nano 33 BLE Sense, (2) a single prototype printed circuit board (PCB) of $40 \times 60mm$, and (3) five Ohmite FSR03CE pressure sensors [5]. The prototype combines both accelerometer and gyroscope data from its internal inertial module (LSM9DS1) [7], with the pressure levels recorded from the FSR sensors, at a rate of approximately 119 measurements per second. This data is then (temporarily) stored in a (FIFO) buffer. When enough data samples have been collected, the data is transferred to the input buffer of the neural network interpreter, which after invocation results in a single classification. Data from this classification is then extracted from the neural network output buffer, and transmitted over BLE, to its connected peripherals.

We gathered the training data set locally, using a Raspberry pi 3 to store the data. This Raspberry pi 3 is tied to the test subject's leg together with a power bank, recording 119 times 11 sensor readouts per second - the 5 pressure sensors, and the accelerometer and the gyroscope with readouts in 3 directions each. We use about $1.5s$, i.e,. 180 records, per frame for activity recognition. The Raspberry Pi is not needed for normal operation.

To meet the requirements for real-time efficient classification we created and tested alternative neural network architectures and space and computation reduction strategies. We employ TensorFlow Lite for Microcontrollers [8] with full-integer quantisation, in combination with the Arduino IDE. We train and test multiple models to classify data frames of about $1.5s$ worth of data (180 lines of sensor outputs). Our most preferred network model is able to do perform classifications between $70ms$ and $80ms$, with an accuracy of 95%, which we deem sufficient for activity monitoring. We note that it is possible to increase the accuracy to 99.6% by enlarging the model, and thereby increasing classification time to the same order of magnitude as the data gathering (about $1.5s$), or to 98.7% in about $0.5s$. However, we prefer the 95% accuracy while being much more real time. Furthermore, our lightweight model takes up less than $9kB$ of space, enabling it to run alongside other software on an embedded system. The entire system uses about $0.10W$ of power, so it can be worn for a long time without the need for recharging.

We show in this demonstration how a tiny neural network can be deployed on an embedded system, to monitor compliance and activities real-time with minimal power usage. During the conference we will:

- Show (live) the design of our AI-enabled prototype smart insoles
- Demonstrate (live) the activity monitoring via small neural network models – either on ourselves or on volunteers from the public with the right shoe-size
- Show (via a poster) the different neural network architectures and techniques tested and how these lead to different trade-offs with respect to accuracy, speed, memory, and energy-usage.

A preview video of the demonstration (including an introduction) is available at `http://roijers.info/vid/bnaic22demo.mkv`.

Acknowledgements This project was supported in part by the KIEM project "Exploration towards an intelligent Scoliosis brace" that was funded by the Stichting Innovatie Alliantie in the Netherlands. This research was in part supported by funding from the Flemish Government under the "Onderzoeksprogramma Artificiële Intelligentie (AI) Vlaanderen" program.

References

1. Abbott, C.A., Chatwin, K.E., Foden, P., Hasan, A.N., Sange, C., Rajbhandari, S.M., Reddy, P.N., Vileikyte, L., Bowling, F.L., Boulton, A.J., et al.: Innovative intelligent insole system reduces diabetic foot ulcer recurrence at plantar sites: a prospective, randomised, proof-of-concept study. The Lancet Digital Health **1**(6), e308–e318 (2019)
2. arduino.cc: Arduino® Nano 33 BLE Sense (February 2022), https://docs.arduino.cc/hardware/nano-33-ble-sense
3. Armstrong DG, Bouton AJM, B.S.: Diabetic foot ulcers and their recurrence. The new England journal of medicine **1**(376), 2367–2675 (2017)
4. Faglia, E., Caravaggi, C., Clerici, G., Sganzaroli, A., Curci, V., Vailati, W., Simonetti, D., Sommalvico, F.: Effectiveness of removable walker cast versus nonremovable fiberglass off-bearing cast in the healing of diabetic plantar foot ulcer: a randomized controlled trial. Diabetes care **33**(7), 1419–1423 (2010)
5. Ohmite: FSR Series (11/20-2), https://www.ohmite.com/catalog/fsr-series/FSR03CE
6. Shu, L., Mai, K.Y., Tao, X.M., Li, Y., Wong, W.C., Lee, K.F., Yip, S.L., Shum, W.H., Chan, W.L., Yuen, C.P., et al.: Monitoring diabetic patients by novel intelligent footwear system. 2012 International Conference on Computerized Healthcare (ICCH) (2012). https://doi.org/10.1109/icch.2012.6724478
7. STMicroelectronics: LSM9DS1 iNEMO inertial module: 3D accelerometer, 3D gyroscope, 3D magnetometer (2015/03), https://www.digikey.de/htmldatasheets/production/1639232/0/0/1/lsm9ds1-datasheet.html
8. Warden, P., Situnayake, D.: TinyML. O'Reilly Media, Incorporated (2019)
9. Zhang, P., Lu, J., Jing, Y., Tang, S., Zhu, D., Bi, Y.: Global epidemiology of diabetic foot ulceration: a systematic review and meta-analysis. Annals of medicine **49**(2), 106–116 (2017)