Integrated Force and Heart Rate Monitor for Quantitative Analysis of Running Training

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***Abstract*—This paper proses an integrated force and heart rate analysis system to enable greater quantitative analysis of running training. By adding an accelerometer to a chest-worn device, which is already commonly used by endurance athletes to track heart rate, we can derive force-related metrics and report this back to the user. This seeks to reduce the incidence of overuse injuries by providing quantitative biomechanical feedback in real-world training scenarios without adding additional burden to the wearer.**

I. Introduction / Background

Running is a highly popular activity performed by a significant proportion of the UK population . Training involves running for sustained periods of time, often at high speeds, which places high mechanical stress on the body due to the vertical ground reaction force (vGRF). Maintaining good running biomechanics allows an individual to effectively use and tolerate these vGRFs, which is critical both for injury prevention and to improve running performance.

Structured training programmes also frequently control exercise intensity in terms of heart rate (HR), which can be measured accurately using device mounted on a chest strap with integrated electrodes. By detecting the QRS complex peaks from the electrode signals, HR can be detected more accurately than through alternative methods such as photoplethysmography (PPG), and hence HR chest straps are commonly used amongst elite and amateur-level athletes.

The widespread use of chest-worn HR straps provides untapped scope to provide force information alongside HR. Accelerometers – devices which measure the acceleration of a body – can provide information about the force travelling through the body, since acceleration is linearly related to force by Newton's Second Law of motion. The chest is a suitable place to house an accelerometer in the context of running since it is close to the body's centre of mass and requires only a single sensor to measure the force for both feet.

Existing analysis suggests that chest-worn accelerometers can effectively segment gait cycles (the period between consecutive steps) and reconstruct vGRF data for each foot strike (shown in Figure 1). Also, they can classify different ground surfaces to allow an individual to objectively track of their training volume on hard/soft/uneven ground. Further, the corresponding HR data can used to analyse the force curve at different intensities and fatigue levels.

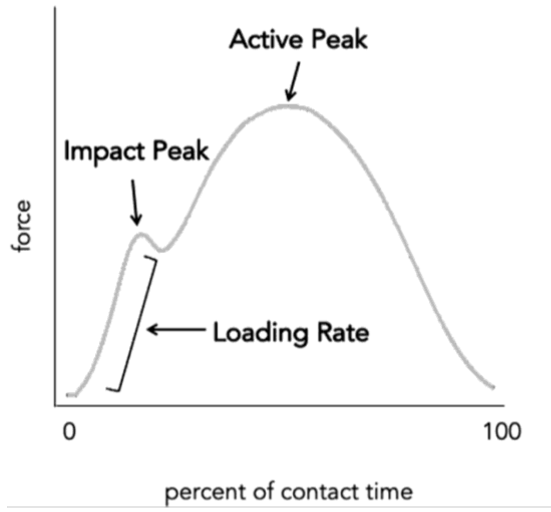

Figure 1 Standard vGRF curve during running, including key clinical features. Figure taken from [1].

This paper therefore suggests a prototype device which incorporates an accelerometer alongside an HR chest strap to derive force and HR information during running, which can improve and inform training programmes without requiring the wearer to purchase a separate device.

II. Related Work

HR monitor chest straps have been used in endurance training since the late 1970s and are widely commercially available [2]. While wrist-based PPG HR monitors are increasingly common, they still lack the accuracy and reliability of chest worn, ECG HR monitors during activity [3]. Frontier X HR monitors provide full ECG traces with live data streaming, however they don't have an accelerometer [4].

Stryd historically produced a chest-worn accelerometer and HR strap, however this produced a 'running power' metric as an alternative method to quantify exercise effort, as opposed to analysing the vGRF. The Garmin running dynamics pod is mounted on the lower back and provides accelerometer-derived metrics of temporal and spatial running parameters, however it doesn't measure vGRF or HR.

In the research domain, vGRF has been accurately recreated during running using accelerometer placed at the sacrum [5] and during jumping using accelerometers placed at the chest, sacrum and back [6]. However, none of these setups included ECG measurement.

III. Imagined or Existing Prototype Sketches/Drawings/Photos

A. General Requirements

The device must measure HR by acquiring and processing an ECG signal and simultaneously record 3-axis acceleration with an accelerometer. It must also store this data for the duration of at least one activity and transmit this data to be analysed offline. It must be comfortable to wear during activity and be able to record for at least 2 hours, though ideally for longer.

B. Components and Materials

- AD8232 signal conditioning block (to extract and process ECG signal)
- ADS1220 analogue to digital converter
- Nordic Semiconductor nRF52832
    - Includes Arm Cortex M4 for processing, 512kB on-chip FLASH and Bluetooth Low Energy for communications
- ADXL380 accelerometer
- Adafruit SPI Flash SD Card - XTSD 512 MB
- Coin cell CR2025 battery holder

All of these components are widely used and easy to source from mainstream suppliers such as Mouser and Farnell.

C. System Overview

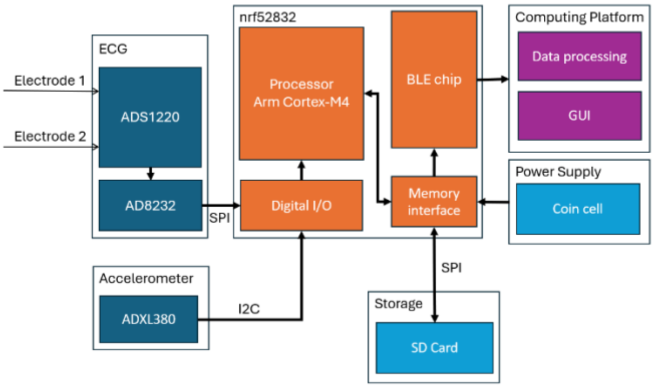

Figure 2 High-level system overview.

Figure 2 shows a high level overview of the system, covering the signal acquisition and conditioning phase (ECG and Accelerometer boxes) to the processing and storage phase (nrf52832 and Storage) to the eventual transmission of the data to the Computing Platform. The system is powered by a CR2025 lithium coin cell which is light and simple to replace.

The acquired electrode and accelerometer signals are transmitted to the CPU (nrf52832) where low-level processing takes place (e.g. identification of ECG QRS complex and hence calculation of heart rate). The data is then sent to the SD card to be stored until the end of the running session.

Once the session is finished, the system will seek to connect to a computing platform and transfer the data from the session. This will be processed by the platform to produce the force and HR metrics and presented in a user-friendly way.

D. Initial Case Design

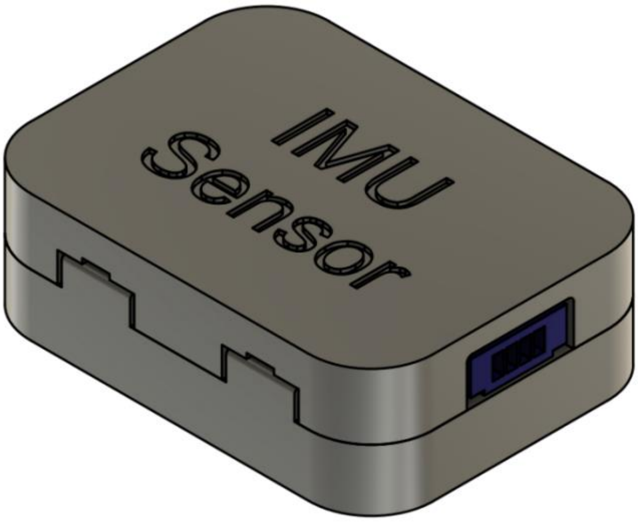

Figure 3 A 3D render of the 3D printed case.

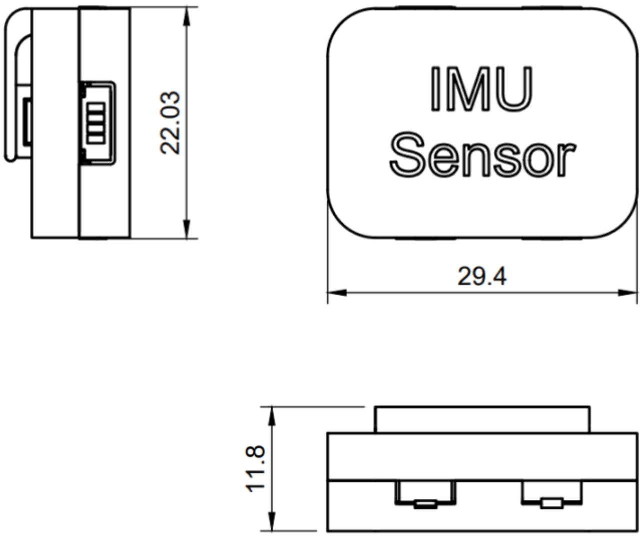

Figure 4 2D CAD design of 3D printed sensor housing.

We made a 3D-printed casing to house our accelerometer board on a chest strap, demonstrated in Figures 3 and 4. Initially, we simply clipped the case onto an elastic heart rate strap and wired it to a development board to transmit the data to the computing platform (shown in Figure 5). Testing as part of a separate study found that the accelerometer data was stable and resilient to motion artefacts.

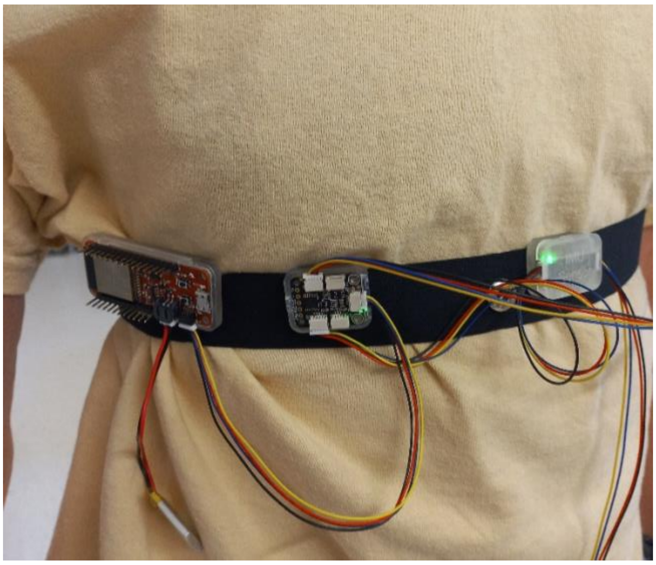

Figure 5 Preliminary system concept test.

With a viable proof of concept for acquiring and transmitting accelerometer data, the next step will be to incorporate our current system with the ECG electronics. By designing a PCB which incorporates the components outlined in Section B and arranged as shown in Section C, we will be able to house the entire system in a (slightly larger) 3D-printed case which can interface directly with the electrodes included in the strap.

E. Software

By performing the data processing on a separate computing platform, we will be able to provide more detailed insights into the force information and temporal-spatial parameters such as cadence, stride times and symmetry between limbs which we can infer from the accelerometer data. This also allows us to add and remove features more easily without needing to alter the on-device firmware.

The on-device software seeks to acquire, store and distribute the data in the most efficient way possible to minimise power and storage requirements. The CPU will process and choose to store store only the HR rather than the full ECG trace to reduce power and storage demands. Further, there is scope to identify periods of unusual activity (e.g. stopping to cross a road or slipping of the chest strap) which can be excluded from storage or transmission.

IV. Responsible innovation

Providing feedback on vGRF experienced during running in the long term should reduce the incidence of injuries, particularly for those who are new to running. This should reduce the risk for those taking up running to stay fit and active, so provides a benefit to public health.

Further development could consider harvesting the kinetic energy from running to power the device, which would reduce the dependence on disposable lithium ion batteries.

V. Author bio(s) / experiences

I am a PhD student focused on developing ear-worn sensors to monitor movement-related disorders. I use data from 9-axis inertial measurement units to analyse activities of daily living, comparing this against data from a gold standard optical motion capture system. My project seeks to incorporate many of the high accuracy metrics from the optical system into the ear-worn system, which is convenient to wear and distribute across a wider range of individuals.

I have also competed to national level in running, which has allowed me to identify areas where technology can improve training methods. This prototype combines the knowledge of inertial sensing I have picked up during my PhD and my background experience in the sport.

VI. Acknowledgements

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VII. References

[1] Agresta, Cristine, et al. "Running injury paradigms and their influence on footwear design features and runner assessment methods: A focused review to advance evidence-based practice for running medicine clinicians." *Frontiers in sports and active living* 4 (2022): 815675.

[2] Burke, Ed, ed. *Precision heart rate training*. Human Kinetics, 1998.

[3] Wang, Robert, et al. "Accuracy of wrist-worn heart rate monitors." *Jama cardiology* 2.1 (2017): 104-106.

[4] Reddy, Satish, et al. "Clinical Validation of a Chest-Worn Personal ECG Device for the Detection of Atrial Fibrillation." *Circulation* 148.Suppl_1 (2023): A16707-A16707.

[5] Kiernan, Dovin, Brandon Ng, and David A. Hawkins. "Acceleration-based estimation of vertical ground reaction forces during running: A comparison of methods across running speeds, surfaces, and foot strike patterns." *Sensors* 23.21 (2023): 8719.

[6] Kerns, Jordan A., et al. "Effect of IMU location on estimation of vertical ground reaction force during jumping." *Frontiers in Bioengineering and Biotechnology* 11 (2023): 1112866.