

Report on TIDAL Network Plus Feasibility Project: Physiological validation of a novel photonic biosensor

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What we set out to discover

Background and research context

Prior to the project we developed a novel photonic sensor for measuring and monitoring muscle activity. The sensor is non-invasive and showed promising results when mounted on the surface of the skin. In addition, the sensor is low-power, and all the components could be miniaturised to create a wearable. Figure 1 shows sensor data acquired synchronously with a ground truth measurement of finger extension and flexion along with electromyography (EMG). The lower sub-plots show raw output from the photonic sensor closely tracking filtered and smoothed EMG magnitude values (MAV). The bottom plot shows the sensor closely tracks ground truth finger flexion and extension.

Optical approaches are the least common method of monitoring muscles, and they are poorly understood [1]. The term optical myography has been used in a variety of contexts and implementations. In a wearable context, there are two feasible approaches where an emitter and a receiver can be used to track muscle activity. In the first, the emitter and receiver are mounted a distance from the skin [2, 3]. In this case, almost all of the light is reflected from the surface of the skin and the sensor acts like a time-of-flight system. The alternative is transmitting light into the body and observing what is reflected [4 – 9]. In the second case, light travels through an unknown number of subcutaneous tissues, each of which contribute to penetration, absorption and scattering influencing the light reflected to the receiver [10, 11].

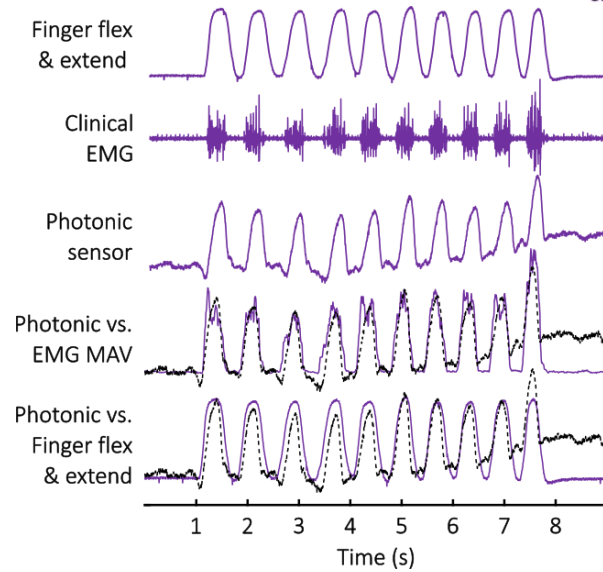


Fig 1: Synchronised recording of clinical grade EMG and optical sensor during finger flexion and extension. Lower plots show photonic sensor tracking EMG mean absolute value (MAV) and finger position.

Engineering / research challenge and why it matters

The explanations for how optical myography systems work are contradictory, ranging from changes in skeletal muscle oxygenation to movement of deep blood vessels [1, 12]. Optical systems typically use Near-Infrared (NIR) light in a spectrum between 650 and 950 nm. Research in the literature has reported limited penetration of NIR through tissue, which would limit the applicability of the approach [13]. In contrast, the same ranges are widely used in optical spectroscopy systems and in optical mammography [14, 15]. The difference in depth penetration is critical; if light can reliably penetrate as far as the epimysium it can be used to track and monitor the movement of muscles under the skin. This approach could provide a cheap and simple alternative to EMG, which would not be susceptible to electromagnetic noise or the influence of sweat.

For this hypothetical sensor to be of value, it would need to function across a range of skin colours and thickness of adipose tissue. The COVID-19 pandemic highlighted optical biomedical sensors can have inherent ethnic biases; the accuracy of pulse oximetry having recently been found to be affected by skin colour [16]. The distribution of adipose tissue is influenced by anatomical location on the body, lifestyle, sex, age, and race-ethnicity [17]. It is therefore important to obtain pilot data to determine how skin pigmentation influences the sensor output.

Aims and objectives for the project

The primary aim of the project was to acquire sufficient data to precisely describe the physiological phenomenon being measured by a novel photonic sensor, which appears to be capable of measuring muscle activity at very low latencies. The secondary aim was to determine to what degree, if any, the photonic sensor was influenced by differences in skin colour. The project objectives were as follows:

1. Perform experiments to determine whether sensor data:
 - a. Accurately measures muscle expansion, as measured using clinical strain gauges.

- b. Is influenced by blood flow to the skin.
 - c. Is influenced by blood flow to the muscle.
2. Compare sensor output to concurrently recorded EMG for a range of skin colours.
3. Image musculature from one or two exemplar participants.

The purpose of objective 1 was to provide insight into the physiological phenomena being measured when monitoring muscle activity. The second objective enabled comparison of sensor output to a gold-standard measure to ascertain the degree to which skin colour would influence sensor performance. The third objective was included to provide ground truth data to validate that muscles were correctly located during experiments.

What we did

We ran three experiments to meet the aims and objectives of the project. The methods are detailed in the following sections.

1. Sensor output when manipulating blood flow

Experiments were performed that focussed on manipulating the flow of blood to muscles and skin in the arm.

Participants

Three participants took part in this part of the study (male, age 25 - 45). Participants provided informed written consent. Ethical approval was granted by the local committee at Newcastle University (ref: 21-029-FRA).

Recordings

Optical sensor data were sampled at a rate of 500 Hz. The optical sensor was placed on the belly of the flexor carpi radialis muscle of the forearm, as located by palpation. The dominant arm was used in all tests. The length of a recording depended on the participant. The average length of a recording was 20 minutes, the maximum length of a recording was 30 minutes.

Protocol: Blood flow to the muscles

A blood pressure cuff (BFR cuff, SAGE fitness) was placed on the upper forearm. A smartphone app wirelessly connected with the BFR cuff was used to control the pressure of the cuff. Prior to any experiments a safety questionnaire associated with use of the BFR cuff was completed through the app. Before starting the experiment, a cuff calibration routine was run, which calculated limb occlusion pressure (LOP).

The participant sat at rest while the operator observed the optical signal. Once the signal was at a steady baseline the experiment began. The participant was instructed to move the index finger of their dominant arm in time with a metronome audio signal running at 2.5Hz. The LOP was then set at 50%. The operator waited for the signal to return to a steady state. The metronome audio cue was then played to prompt the participant to move their finger. The cuff was then deflated. After waiting for the optical signal to return to baseline the participant was again prompted to move their finger via the metronome. This procedure was then repeated for an LOP of 80%.

Protocol: Blood flow to the skin

The belly of the flexor carpi radialis muscle of the forearm was located via palpation. The area was lightly marked with ink. Warm water was used to heat the arm and the optical response was observed as the arm cooled. A water bath was set to around 40° Celsius. The participant submerged their arm

for between 10 to 15 minutes. The arm was removed from the bath and after a light drying the sensor was placed over the belly of the flexor carpi radialis muscle. Optical data was acquired for 20 minutes while the arm cooled.

2. Sensor output comparison across skin tones

A capacitive sensor was sourced that enabled us to conveniently stream a proxy measure of force produced by individual fingers. Because the sensor provided a more direct measure of finger force than EMG, and the signal to noise ratio (SNR) of the optical signal can be calculated independently of EMG, this sensor was preferred. The sensor was integrated with an existing Python platform for biomedical signal acquisition [18].

Participants

Twenty limb-intact participants and one limb-different participant took part in this part of the study. Participants provided informed written consent. Ethical approval was granted by the local committee at Newcastle University (ref: 21-029-FRA).

Recordings

Finger position data were recorded using an Etee virtual reality controller (TG0, UK). Data were sampled at 100 Hz. In the case of the participant with limb difference, ground truth finger position was recorded from the contralateral hand and the participant was instructed to perform mirrored movements with their residual limb.

Optical sensor data were sampled at a rate of 500 Hz. In the case of limb intact participants, the optical sensor targeted the flexor digitorum superficialis. The muscle site was located via palpation. In the case of the limb different participant the sensor was placed targeting the muscles typically used for prosthesis control.

Electromyography data were recorded for the limb different participant. Data were acquired using a Trigno Quattro sensor (Delsys, USA). Data were sampled at 2000 Hz. Electrodes were placed close to the muscle targeted by the optical sensor.

Protocol

Skin tone was mapped using a digital camera (Canon EOS 1200D). Participants stood beside a colour correction palette commonly used in photography in a light-controlled room. Data were sampled from colour corrected images of the anterior forearm and recorded using the CIELAB colour space [19]. A skin tone sampling image taken for participant 5 is shown in Figure 2.

Experimental task

The experimental task was explained to participants by the operator before they began. At the start of the experiment participants were at rest with their arm supported. The operator then played a series of audible beeps in 10 second bursts. The beeps were presented at a rate of 2.5 Hz and acted as a digital metronome. Participants were instructed to perform the task with their index finger. The task was to move the finger specified in time with the metronome, tapping the virtual reality controller and extending the finger between beeps. After the beeps played for 10 seconds the participants were given a period to relax. During the experiment, a real time plot showing synchronised sensor data from each of the recording modalities was displayed to the experimental operator.

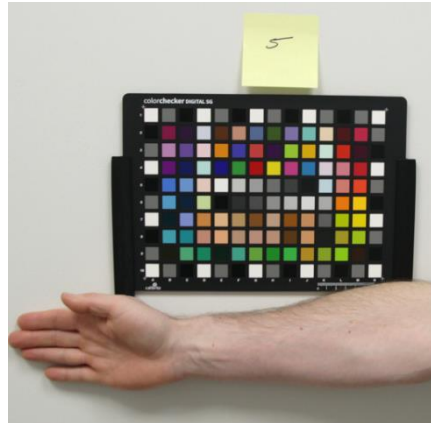


Fig 2: Sample colour correction palette image from participant 5.

Analysis

The primary measure of signal quality was the SNR. Signal to noise was calculated based on the ratio of the power of the signal that could be attributed to the desired frequencies vs the power attributed to all other frequencies. Designed frequencies were defined as those below 5 Hz. Optical data was filtered using a 4th order high-pass Butterworth filter at 1 Hz to remove signal drift. All SNR data was assumed to be non-parametric when any comparisons were made across participants.

What we found

1. Sensor output when manipulating blood flow

The relationship between blood pressure cuff limb occlusion and the optical response are shown in Figure 3. The image shows that limb occlusion induces a drift in the raw optical signal, and this is the result of reduced blood flow (deoxygenation) to the arm. Finger movement is visible in the raw signal. The drift induced by changes in blood pressure can be removed by filtering, as shown on the fourth row of Figure 3. The bottom row shows a time frequency representation of the filtered optical signal. The darker colours aligned with movement demonstrate that response occurs at 2.5 Hz.

No relationship was found between blood flow and the skin and sensor output. Over a temperature difference equivalent to transitioning from a warm bath of around 40° Celsius no trends were observed in the sensor output greater than the baseline noise. As no trends were observed we have refrained from displaying the results.

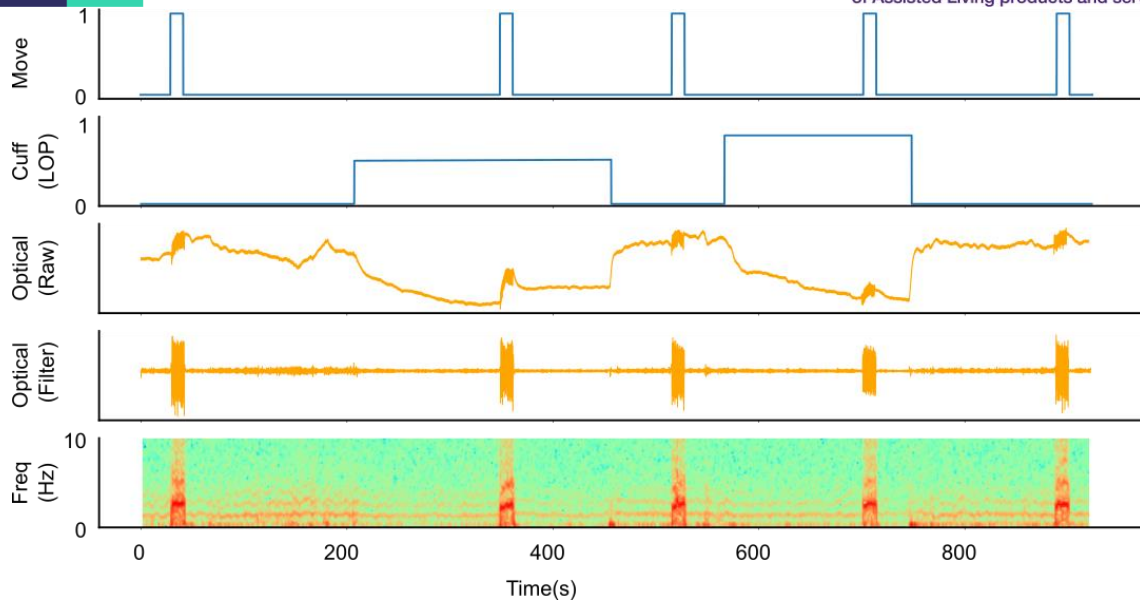


Fig 3: Relationship between cuff pressure, optical signal and filtered optical signal over time. Top row shows cued periods of movement. Second row shows percentage limb occlusion pressure (LOP). Third and fourth rows show raw and filtered optical signals, respectively. Bottom row shows the time frequency of filtered optical response over the period.

2. Sensor output comparison across skin tones

The experimental task used is validated in Figure 4. Figure 4 shows a sample response from a single participant. The top row of the figure shows finger tracking data obtained from the Etee capacitive sensor. Data representative of finger tracking induces a corresponding response in the optical signal shown in the middle row. The bottom row shows the corresponding time frequency response for the optical signal overall and for time periods associated with each of the fingers. It can be observed that the predominant frequency in the finger response data is at 2.5 Hz. Therefore, the optical signal produced matched the frequency of the audible cue used.

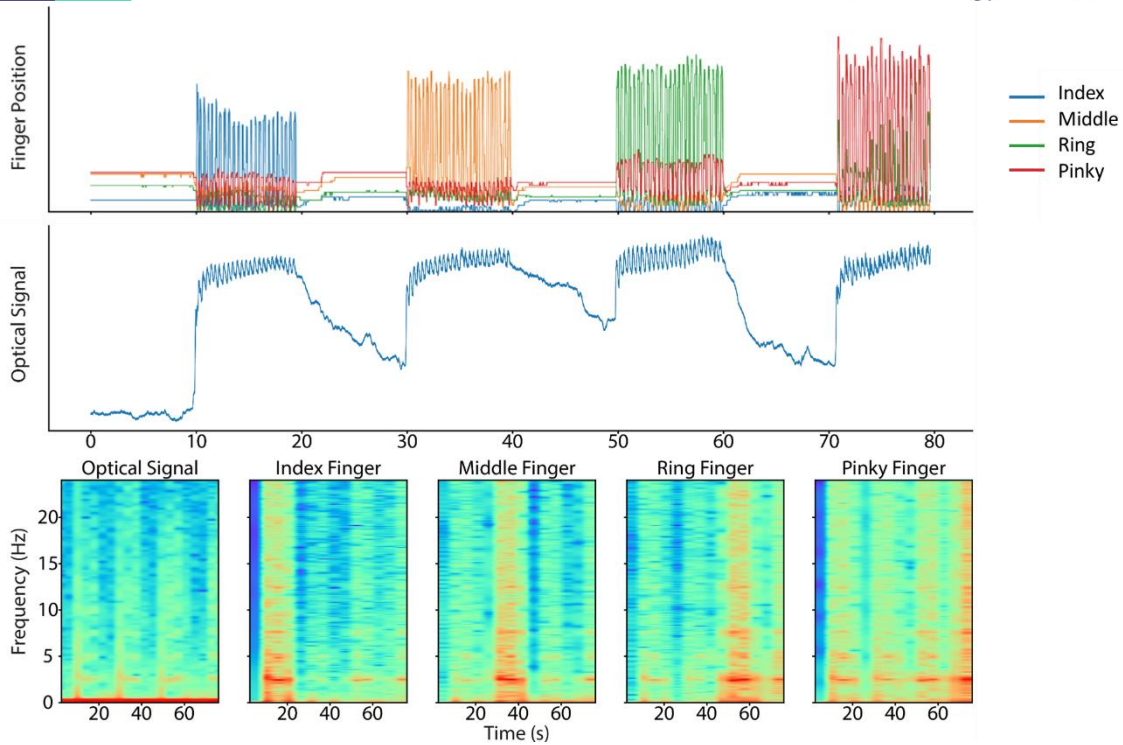


Fig 4: Validation of the experimental task. Top row - tracking of individual fingers using capacitive Etee virtual reality controller. Middle row - corresponding optical signal demonstrating signal temporally aligned to finger position. Bottom row – time frequency response of overall signal and individual fingers. Results show a peak at 2.5 Hz corresponding to the audible metronome cueing task.

The effect of skin tone on the optical signal is shown in Figure 5. A strong positive correlation was found between skin tone and the baseline value of the optical signal when the participant is at rest ($r = 0.63$, $p < 0.01$), as shown on the left side of Figure 5. The image on the right side of Figure 4 shows no correlation was found between skin tone and the optical signal SNR ($r = 0.06$, $p = 0.79$).

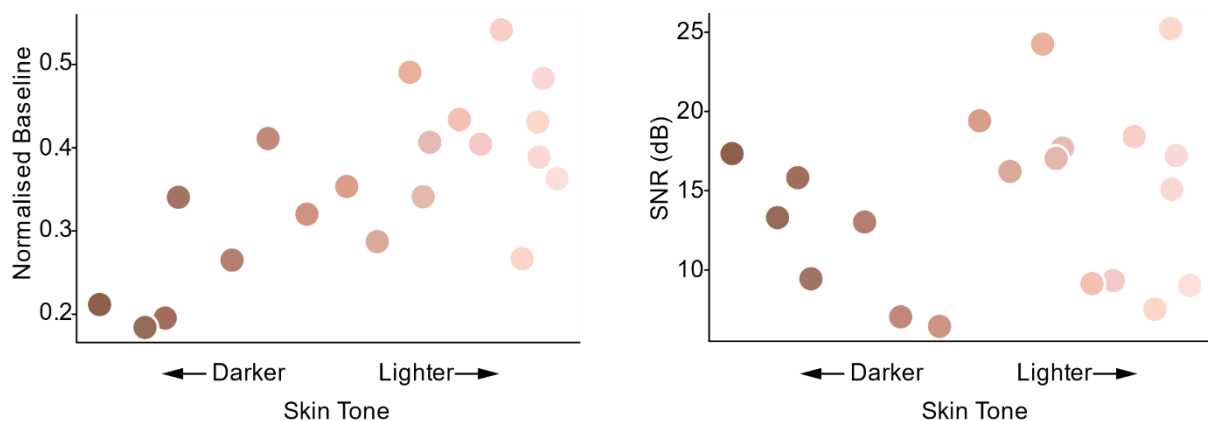


Fig 5: Relationship between skin tone and sensor properties. Left image shows skin tone is highly correlated to the normalised baseline level of the sensor. Right image shows skin tone is not correlated to the signal SNR.

What this means

1. Sensor output when manipulating blood flow

The results of the experiments manipulating blood pressure show that the output of the sensor is influenced by oxygenation and deoxygenation of tissues in the arm. Changes in blood oxygen content induce a predictable drift pattern. Fortunately, the rate of change in the drift pattern are such that they may be removed using standard filtering procedures, typical to most biomedical data acquisition systems. The results of filtering are shown in the results section. The filtered signal retains a flat baseline and retains a strong signal to noise ratio, as demonstrated by the 2.5 Hz response in Figure 3. Results of the second experiment demonstrate that the signal is unlikely to be impacted by changes in superficial blood flow to the skin. This means the sensor will not be impacted by temperature changes. Taken together, these results all suggest that the optical sensor is relatively robust to the most likely physiological sources of artefacts.

Overall, safe manipulation of blood flow to the arm was more difficult to control than anticipated. To address this the team developed an alternative method of removing baseline drift based on coupled optical sensors. This method has been piloted and we are confident acquiring data from the second-generation version of the sensor will provide better data for publication. The team will acquire this data once the new version of the sensor is ready for use.

2. Sensor output comparison across skin tones

The results obtained from the second set of experiments are very promising. Although skin tone influences the normalised baseline activity produced by the sensor, it does not appear to influence the SNR of the sensor. Generally, in a control context, actual baseline values are arbitrary if baseline drift can be removed after preprocessing a stationary signal at any given range can be normalised. No correlation between skin tone and SNR provides strong pilot data suggesting the sensor will have wide applicability going forward.

What next

Repeat blood pressure calculations

The team devised an alternative method of taking blood pressure measurements using multiple sensor sites, which we believe will be more accurate than the current method. Sample data has been acquired validating that some signal drift can be eliminated by sampling from two optical sensors concurrently. Blood pressure calculations will be repeated using our second-generation optical sensor. The second-generation sensor is high density allowing an arbitrary number of sensor sites to be sampled in parallel, with up to 64 in the current model.

Publications

Two conference papers have been accepted to the 2024 Myoelectric Control Symposium (MEC) [20, 21]. One journal paper is drafted, which may use some of the data reported here and will be attributed to TIDAL N+. A second journal paper will be written focussed on these results.

Funding

We will apply for further funding based on this pilot data and the blood pressure calculation data we obtained using the next generation sensor system.

Commercial

We have had interest from one potential commercial partner and have worked with them to investigate whether a supply chain can be established to produce the sensor at lower-costs and higher quantities. These discussions were based on the first-generation sensor. A second potential commercial partner has requested a demonstration of the sensor.

Additional work

Our original goal was to perform analysis based on a very narrow emission source at 800nm. This spectrum is known as the isosbestic point between oxyhemoglobin and deoxyhemoglobin. By comparing results from an LED (a non-coherent light source) with a laser (a coherent light source) we aimed to gain a better understanding of the depth to which light penetrates the skin at different intensities. The results generated so far suggest optical myography systems penetrate the skin. The planned experiment would allow us to calculate the depth of penetration, which would provide insight into the degree of lateral spread of light within tissue. This would inform methods for developing high density imaging systems.

A specialist spectrometer capable of characterising the spectrum of an 800nm LED source within a very tight spectrum was ordered. When acknowledging the order, the supplier promised a prompt delivery time. Unfortunately, this was not the case with delivery after a significant delay of around 2 months. When it became clear that the work could not proceed, we pivoted away from building the rig required for the original experiment and instead focussed on repeating the blood pressure calculations originally outlined in *what next* report.

What we did

A second-generation optical sensor was completed. This sensor is a modular multi-channel design which can be stacked to all incremental channel counts. A rudimentary time domain multiplexing method was used to sample data at 100 Hz. The new system enabled synchronised recording from multiple sites. An image of the system is shown in Figure 6. We repeated the blood pressure

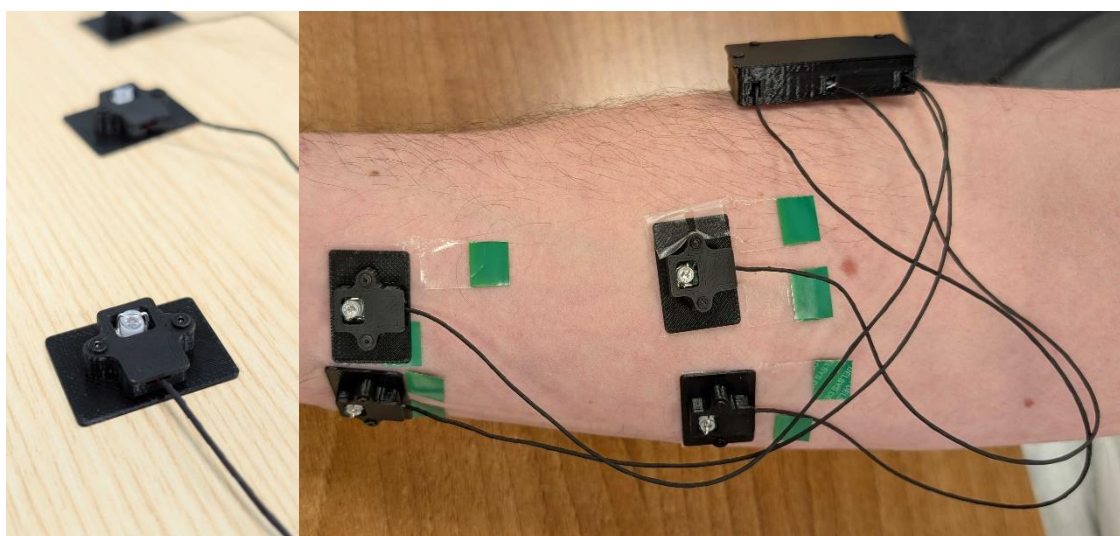


Fig 6: Second-generation sensor design using modular sensing sites. Left image shows sensors. Right image shows sensors mounted to inner arm and sensor control unit.

experiments using variations of the second-generation optical sensor system, focussing on the how the raw signal was impacted by drift.

What we found

The relationship between cuff pressure and three optical signals acquired in tandem using the updated optical system are displayed in Figure 7.

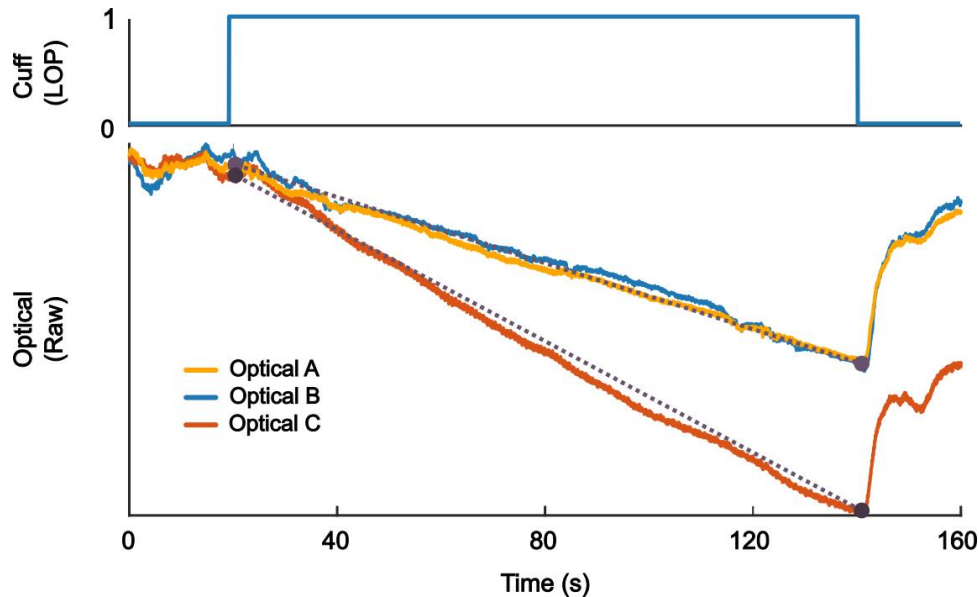


Fig 7: Limb occlusion over time measured across three sensing sites. Upper axes show percentage limb occlusion pressure. Lower axes show optical signal recorded at three sites.

The signals differ from those submitted in the initial report in two ways:

1. The relationship between all the raw optical signals and limb occlusion over time is far more linear than that displayed in Figure 3.
2. Optical signal A and optical signal B share an almost identical response to limb occlusion.

A first assumption would be that optical signal A and optical signal B were recorded in close proximity, while optical signal C was further away. In reality, optical signal A was closer to optical signal C, but optical signal A and optical signal B both sampled from the skin above the same muscle group (at a greater distance). Our working hypothesis is that signal drift induced by deoxygenation of the arm is strongly influenced by the composition of muscle and tissue under the sensing site. Sensors placed along the same muscle group can produce highly correlated signals in response to changes in blood pressure.

What this means

The updated system has a far more predictable response to changes in blood pressure than the initial sensor. Our tests suggest the underlying skeletal structure of the arm plays a significant role in the raw signals observed in response to changes in blood pressure. When blood pressure changes, optical channels with the same underlying tissue and muscle structure produce signals which can be automatically clustered.

From a signal processing perspective, we anticipate this means high density optical sensing could adopt or adapt spatial filtering methods typical in electroencephalography, such as common average referencing and or Hjorth's surface Laplacian. The implication of using spatial filtering to remove

common signal drift is a reduced reliance on temporal filtering. A reduced reliance on temporal filtering means that the optical signal can capture a wider range of frequencies of muscle movement, and / or retain the raw envelope-like shape displayed in response to movement in the raw signal.

Publications

A journal paper is currently in submission. A second paper is being drafted.

Funding

Once blood pressure calculation data are obtained from a sufficient number of participants we will apply for further funding.

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Appendix 1

Carbon calculations for travel undertaken as part of the project

Trip 1: Rothbury to Salford (return)

Transport: Car

Miles: 350

Carbon calculated: **83.8 KG CO₂ e**

Trip 2: Newcastle Upon Tyne to Welwyn Garden City (return)

Transport: Train

Miles: 496

Carbon calculated: **35.45 KG CO₂ e**