A Manual Obstruction

We manually obstructed the artery before the measurements site (i.e. obstructing at a location preceding the arrival of the blood to the measured site). Fig 2-1 show the IPG signal for obstruction of the ulnar artery, above the elbow (with gel electrodes) and the obstruction of the radial ulnar below the elbow (with dry electrodes) respectively. We observe an increase of the baseline impedance Z, reflecting on the artery narrowing, during obstruction. The increase in baseline was a common denominator in both the fist clenching and Strack protocols during muscle activation. In terms of the pulsation amplitude, ΔZ, for the obstruction above the elbow (Fig. 2), there were no detectable pulses, most likely due to the magnitude of the force required to obstruct the artery in that area (effectively blocking the flow). For obstruction close the measurement site (Fig. 1) we see a decrease in pulsation amplitude.

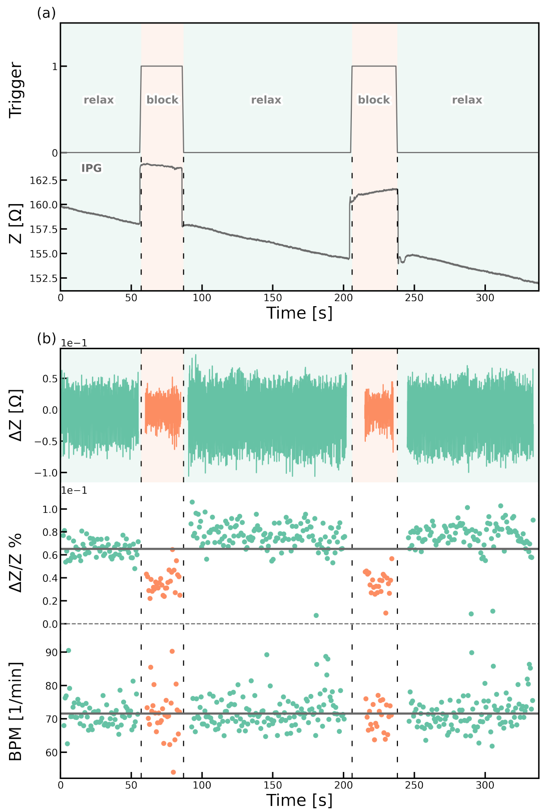

Fig. 1 IPG response to manual obstruction. **(a)**. Trigger signifying when the artery was obstructed (top) and 4-terminal IPG signal at the radial artery as a function of time (bottom). **(b)**. Running average of the impedance as a function of time (top), relative impedance changes as a function of time (middle), BPM as a function of time (bottom). Vertical dashed lines signify a transition between states and solid black line the average at first relaxation period. Only data from detectable pulses are shown.

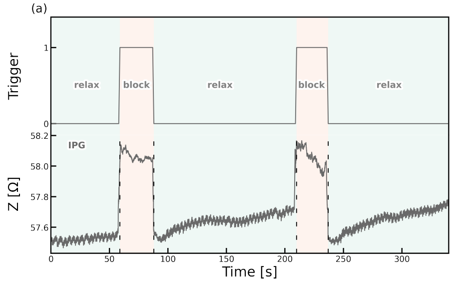

Fig. 2 IPG response to manual obstruction. **(a)**. Trigger signifying when the artery was obstructed (top) and 4-terminal IPG signal at the ulnar artery as a function of time (bottom).

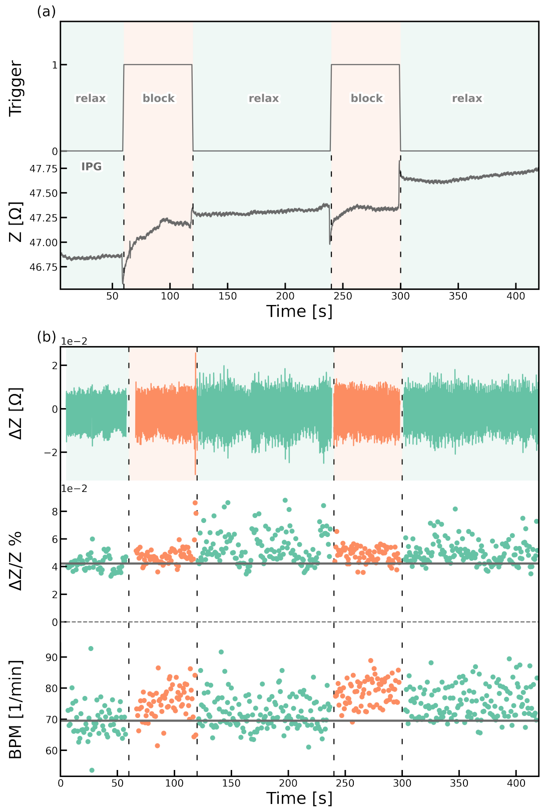

Fig. 3 IPG response to manual obstruction. **(a)**. Trigger signifying when the artery was obstructed (top) and 4-terminal IPG signal at the radial artery as a function of time (bottom). **(b)**. Running average of the impedance as a function of time (top), relative impedance changes as a function of time (middle), BPM as a function of time (bottom). Vertical dashed lines signify a transition between states and solid black line the average at first relaxation period. Only data from detectable pulses are shown.

We also obstructed the artery after the measurement site (i.e. obstructing at a location succeeding the arrival of blood to the measured site). For such an obstruction we observed a decrease in the baseline impedance (Fig. 3), reflecting on an increase in the radius of the artery.

B Fist Clenching (Carbon)

We repeated the first clenching protocol with carbon electrodes (Fig. 4). As with the gel electrodes, we see a dramatic increase in the baseline impedance Z, as well as a slight increase in the pulsation amplitude ΔZ, during fist clenching. After the release, we observe a sharp decline in the pulsation amplitude followed by a gradual return to baseline. Fig. 5 shows a detailed comparison of the behavior of the pulsation amplitude between the measurements obtained by the gel and dry electrodes. Overall, the trend of the pulsation amplitude is the same for both measurements.

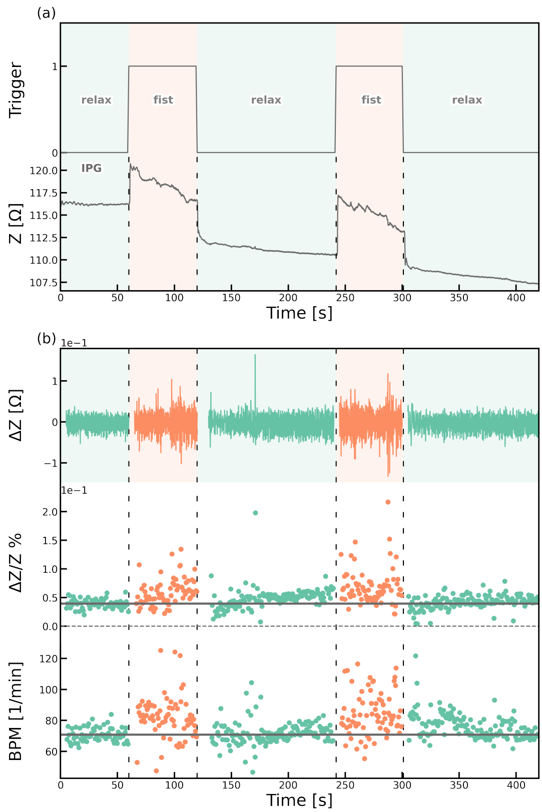

Fig. 4 IPG response to fist clenching. **(a)**. Trigger signifying when fist clenching occurred (top) and 4-terminal IPG signal at the ulnar artery as a function of time (bottom). **(b)**. Running average of the impedance as a function of time (top), relative impedance changes as a function of time (middle), BPM as a function of time (bottom). Vertical dashed lines signify a transition between states and solid black line the average at first relaxation period. Only data from detectable pulses are shown.

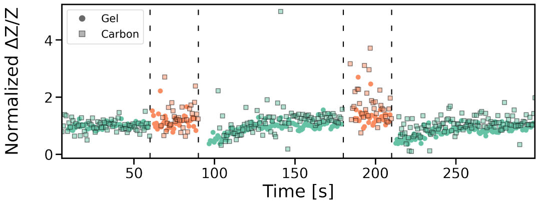

Fig. 5 Gel and dry (carbon) comparison during fist clenching: Normalized relative pulsation amplitude as a function of time. Opaque circles mark gel electrode measurements, transparent squares mark dry (carbon) electrode measurements

C Stracks and Expressions

The Strack protocol was repeated for each subject and across different subjects. The results of the different sessions are presented below. Overall, similar behavior is shown: during muscle activation there is an increase in baseline impedance Z (decrease in artery radius), with the pulsation amplitude ΔZ varying over different repetitions.

We make special note of Fig. 13 - 14. In these Strack sessions, the subject spontaneously yawned during one of the relaxation segments. For both occurrences, while yawning, the baseline impedance increased, and the pulsation amplitude ΔZ decreased.

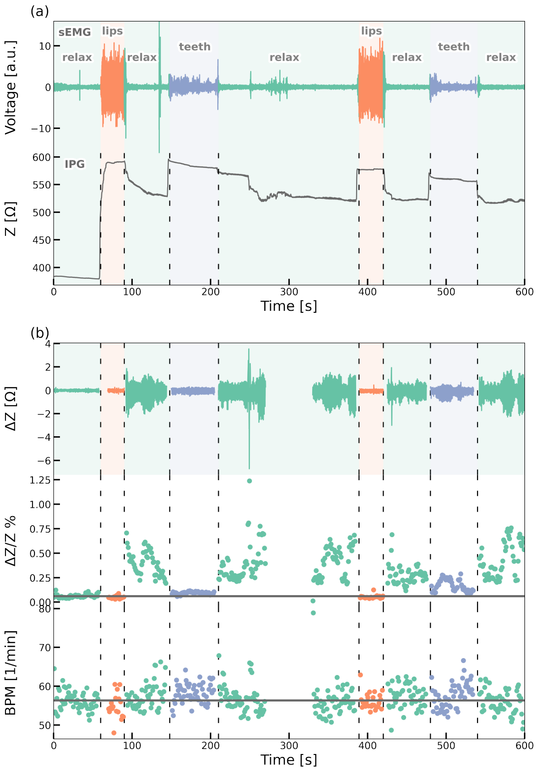

Fig. 6 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

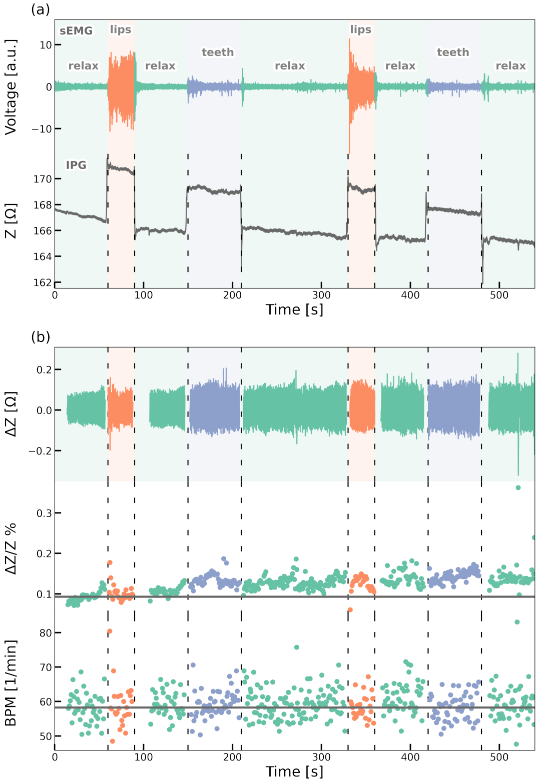

Fig. 7 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

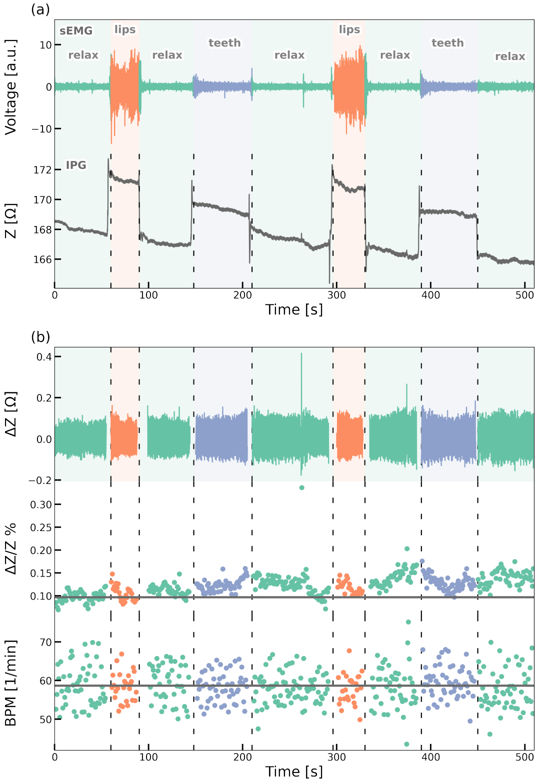

Fig. 8 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

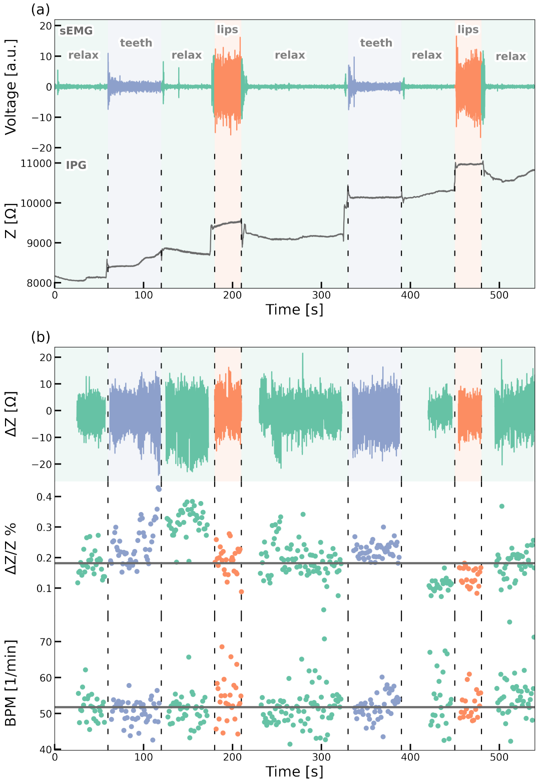

Fig. 9 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

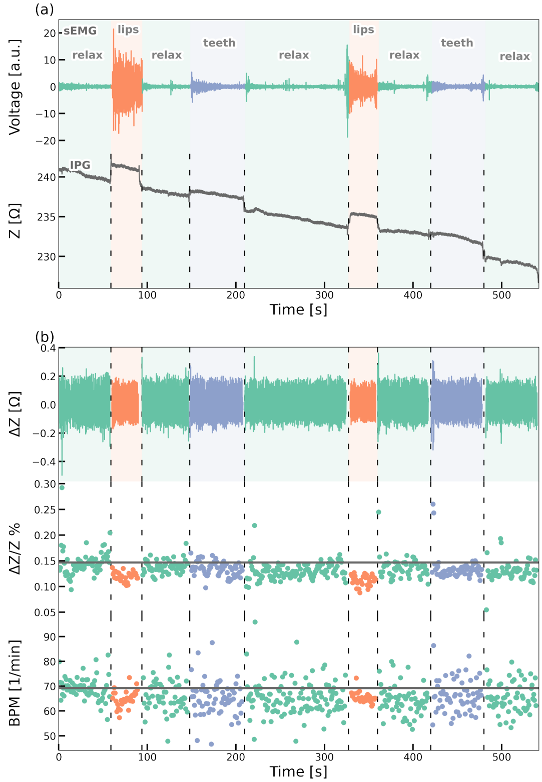

Fig. 10 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

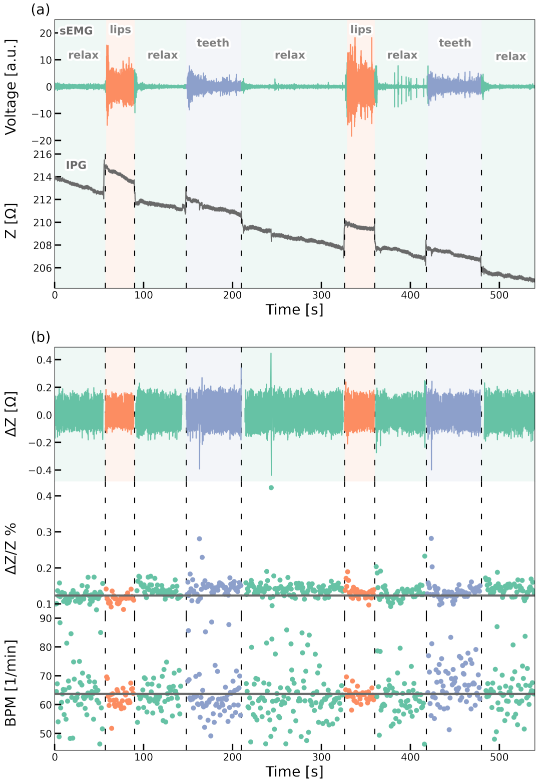

Fig. 11 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

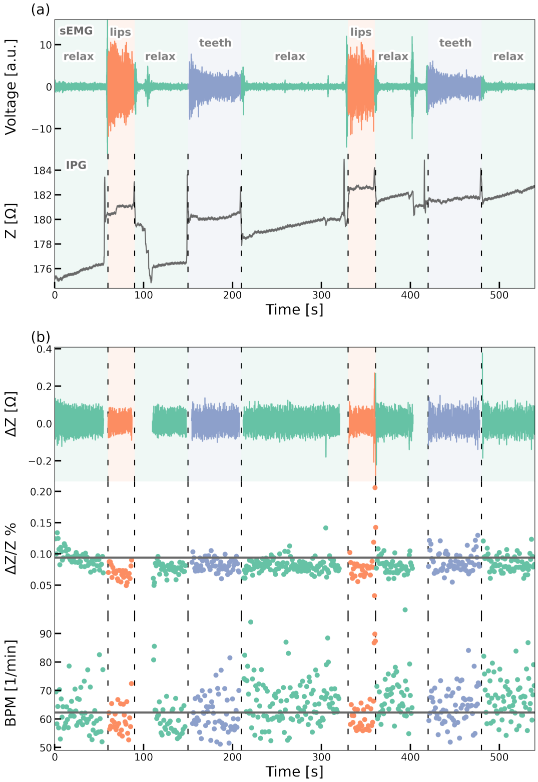

Fig. 12 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

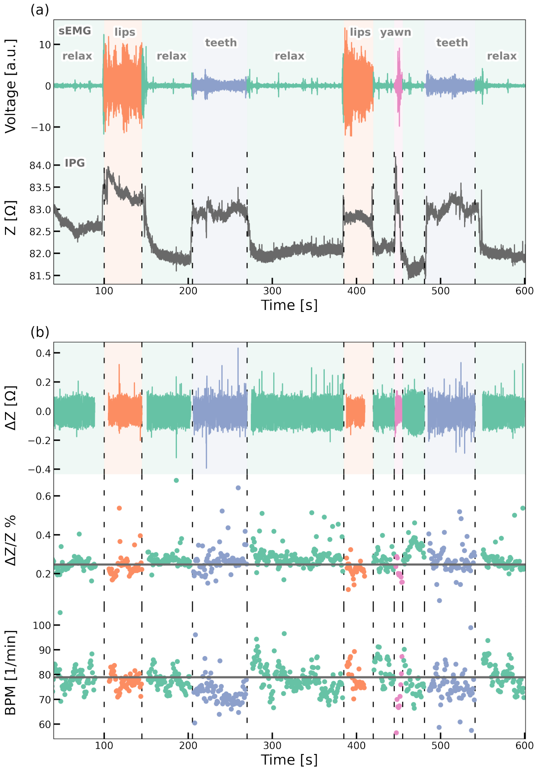

Fig. 13 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

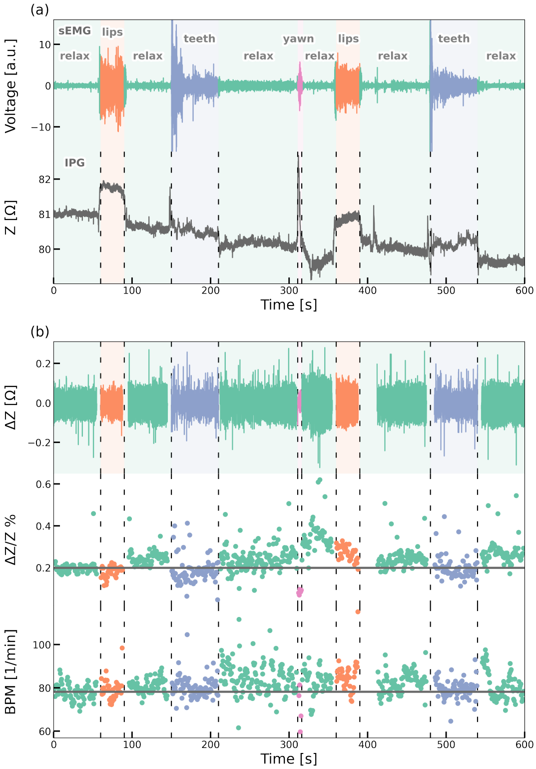

Fig. 14 sEMG and IPG response to Strack conditions (lips and teeth). (a). sEMG activity versus time (most intense ICA source during the "lips" condition) and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

Participants were also instructed to perform various facial expressions: small smile, big smile, genuine smile, anger, sadness, happiness, surprise, disgust and contempt. For 'genuine smile' participants were asked to think of something that brings that joy. sEMG and IPG measurements of expressions are presented in the following.

In most cases the baseline impedance increased during facial expressions, with the exception of 'Disgust' and 'Anger' for some participants. This behavior was exhibited in Fig. 3 when blocking the artery after the flow. The change in the qualitative behavior of the baseline impedance (the increase or decrease of the artery radius), marks the impact of different muscle activations on blood flow. In terms of the pulsation amplitude, similarly to Strack we see variability in the changes of ΔZ.

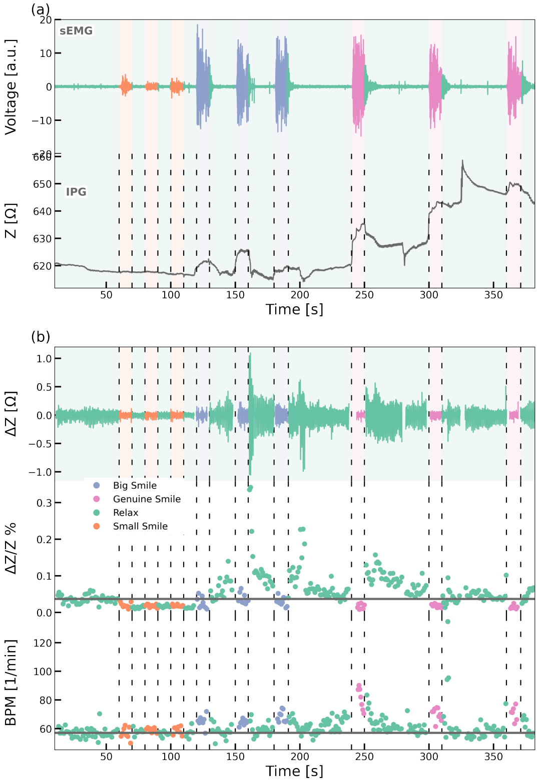

Fig. 15 sEMG and IPG response to Expressions. (a). sEMG activity versus time and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

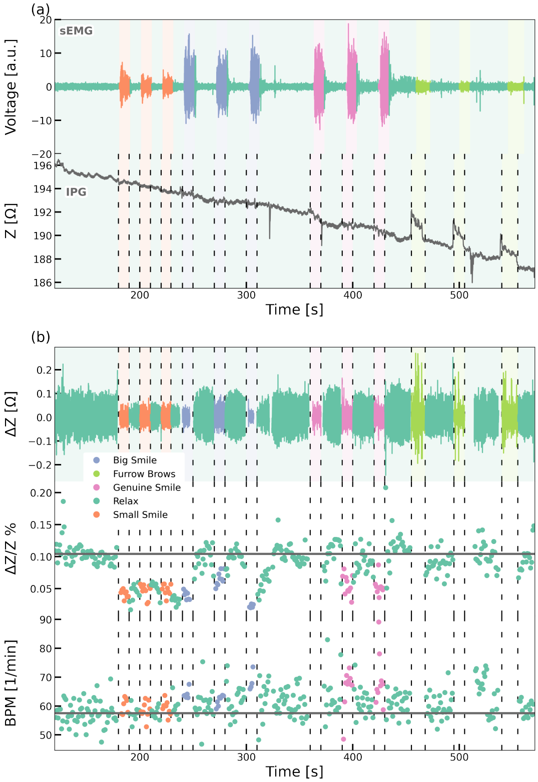

Fig. 16 sEMG and IPG response to Expressions. (a). sEMG activity versus time and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

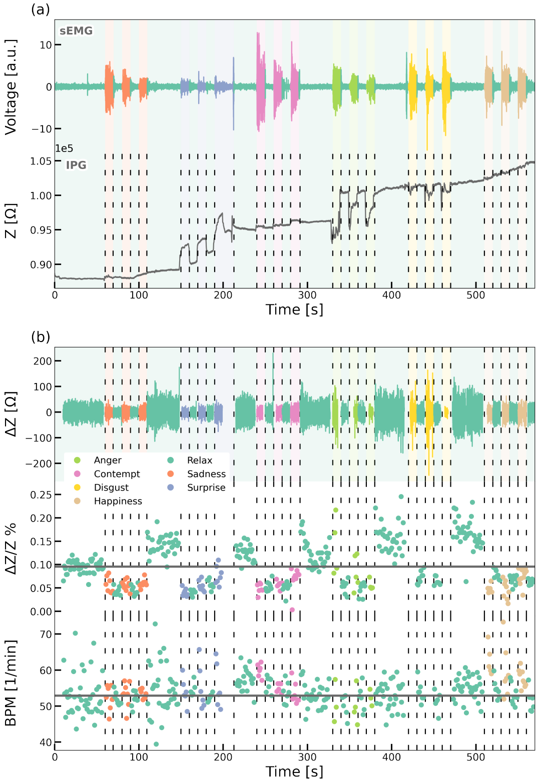

Fig. 17 sEMG and IPG response to Expressions. (a). sEMG activity versus time and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

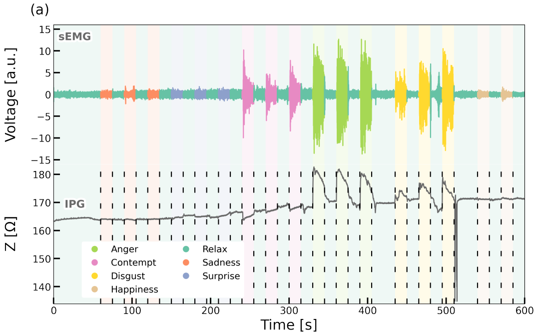

Fig. 18 sEMG and IPG response to Expressions. (a). sEMG activity versus time and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

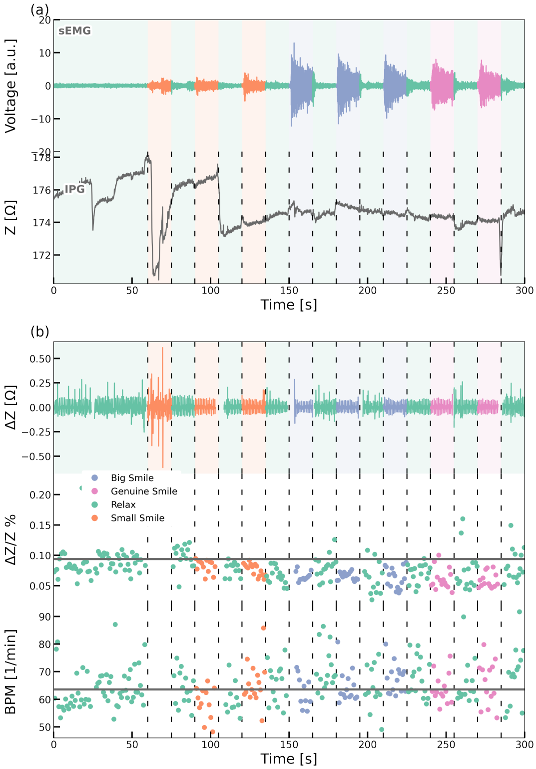

Fig. 19 sEMG and IPG response to Expressions. (a). sEMG activity versus time and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

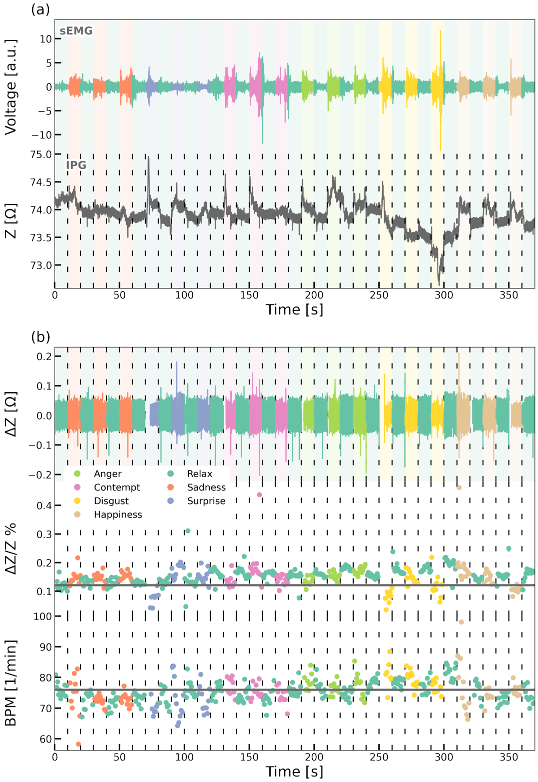

Fig. 20 sEMG and IPG response to Expressions. (a). sEMG activity versus time and 4-terminal IPG signal at the temporal superficial artery versus time (bottom). (b). Running average of the impedance versus time (top), relative impedance change versus time (middle), and beat per minute (BPM) versus time (bottom). Dashed lines signify a transition between states and the solid black line is the average at the first relaxation period.

D Variability of Muscle Activation

We present the variability in source distribution in Fig. 21. Each ICA source is distributed across all three activiations (fist, lips and teeth), and centered around their average intensity (rank 0). All source distributions are overlayed, such that opaqueness in a certain rank signifies multiple distributions in said rank. We see for the fist a very narrow distribution of all the sources, with most of them clustered around rank 0 (average intensity). This is in contrast to the lips and teeth condition, where the distributions are more spread out: we see both more ranks occupied, as well as the decrease in opaqueness around rank 0. Lastly, the average variability of all source distributions is displayed in the figure of each activation: 0.58 (fist), 1.6 (lips) and 2.0 (teeth).

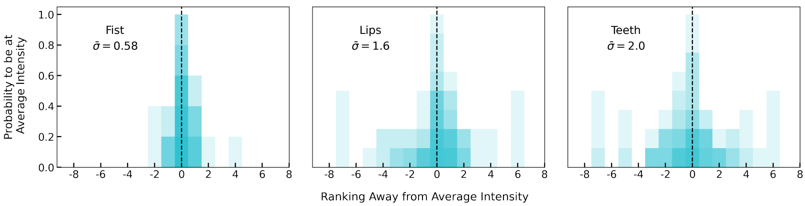

Fig. 21 ICA Source Variability Across Repetitions. The probability of a source to be at its average intensity (i.e. rank 0) for the different activiations: fist clenching (left), strack 'lips' (center) and 'teeth' (right) condition. All 16 sources are overlayed on top of one another such that the more opaque the color in a certain bin, the more sources are distributed in said bin.

E IPG Model

The 4-terminal bio-impedance Z is determined by the artery impedance, Z_a, and the impedance of the surrounding tissue, Z_t (Eq. 1).

$$1/Z = 1/Z_a + 1/Z_t \Rightarrow Z = Z_a Z_t/(Z_a + Z_t) \tag{1}$$

Owing to the tube-like shape of blood vessels, the impedance of the artery can be modeled as a cylindrical resister. Thus, the dependence of Z_a on the artery radius (r_a), length of the measured segment (l) and the blood resistivity (ρ) is given by (Eq. 2).

$$Z_a = \rho l/A = \rho l/(\pi r_a^2) \tag{2}$$

Therefore, when comparing the baseline impedance before, during, or after an action, we can deduce whether the radius of the artery changes. In particular, assuming the blood resistivity ρ and tissue impedance Z_t remain constant, if the baseline impedance Z increases, then the radius of the artery r_a decreases.

The overall bio-impedance is also sensitive to blood pulsation and can be therefore described by a baseline impedance (Z) and ΔZ - the change in the impedance due to pulsation. ΔZ can be expressed by Eq. 3 [1].

$$\Delta Z = \pi Z^2 \Delta {r_a}^2/(\rho l) \tag{3}$$

where $\Delta r_a = \sqrt{r_a'^2 - r_a^2}$ is the (artery) radius pulsation amplitude change.

Thus, a change in baseline pressure (e.g. during artery blockage) would result in changes in artery radius r_a, as well as the radius pulsation amplitude Δr_a:

$$\Delta r_a = \sqrt{\rho l \Delta Z}/\sqrt{\pi Z^2} \tag{4}$$

Whether Δr_a will increase or decrease (during or after a certain action) can be inferred from changes observed in ΔZ and Z. If ρ is constant, the ratio between the final and initial Δr_a is given by:

$$\Delta r_a'/\Delta r_a = \sqrt{\alpha}/\beta \tag{5}$$

with $\alpha = \frac{\Delta Z'}{\Delta Z}$, the relative increase in ΔZ, and $\beta = \frac{Z'}{Z}$, the relative increase in Z.

Increase in pressure leads to an increase in Z and $\beta > 1$. α on the other hand may be smaller or bigger than 1, reflecting the viscoelastic properties of the artery. Even when α does increase, altogether Δr_a may increase or decrease, depending on the link between r_a and the pressure. As arteries are known to be viscoelastic, this relationship is expected to depend on pressure in a non-trivial manner [2], this is simplistically conveyed by Eq. 5 (Fig. 22).

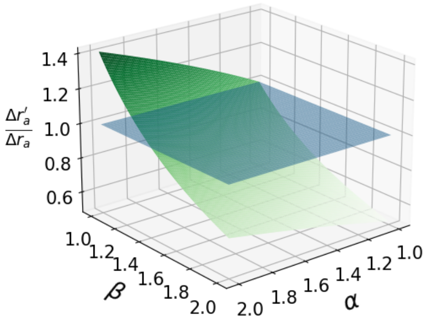

Fig. 22 Relative Pulsation Artery Radius Change. Dependency of the increase or decrease in the artery radius pulsation change Δr_a as a function of the relative change in Z (depicted by β) and ΔZ (depicted by α). The condition for increase in Δr_a is marked by the blue plane (above Δr_a increases, below it decreases).

References

[1] NYBOER J, Kreider MM, Hannapel L. Electrical Impedance Plethysmography. Circulation. 1950;2(6):811–821. https://doi.org/10.1161/01.CIR.2.6.811.

[2] Neutel CHG, Corradin G, Puylaert P, De Meyer GRY, Martinet W, Guns PJ. High Pulsatile Load Decreases Arterial Stiffness: An ex vivo Study. Frontiers in physiology. 2021;12:741346–741346.