Bioimpedance-Based Detection and Quantification of Venous Outflow Responses During Controlled Pneumatic Augmentation

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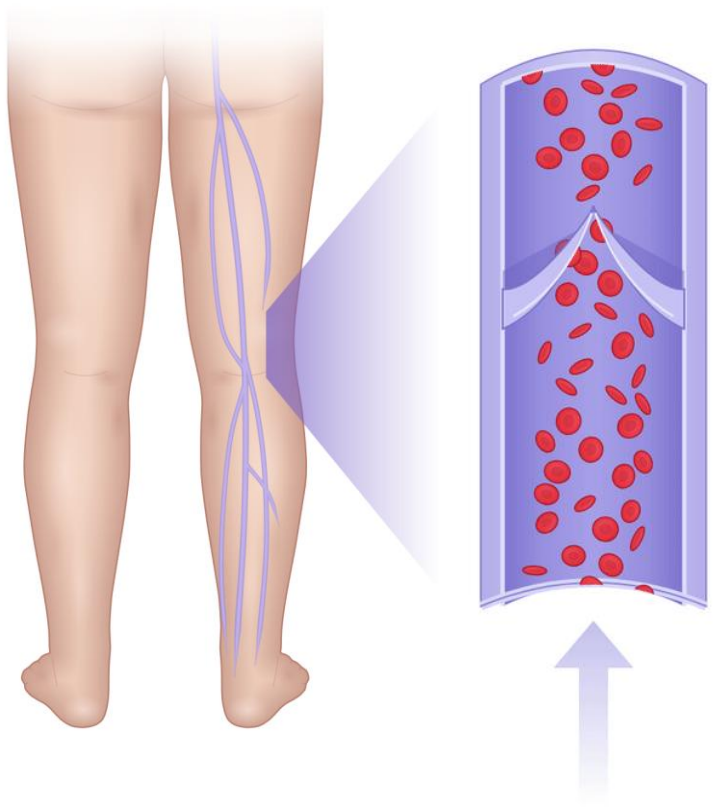
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Deep venous system

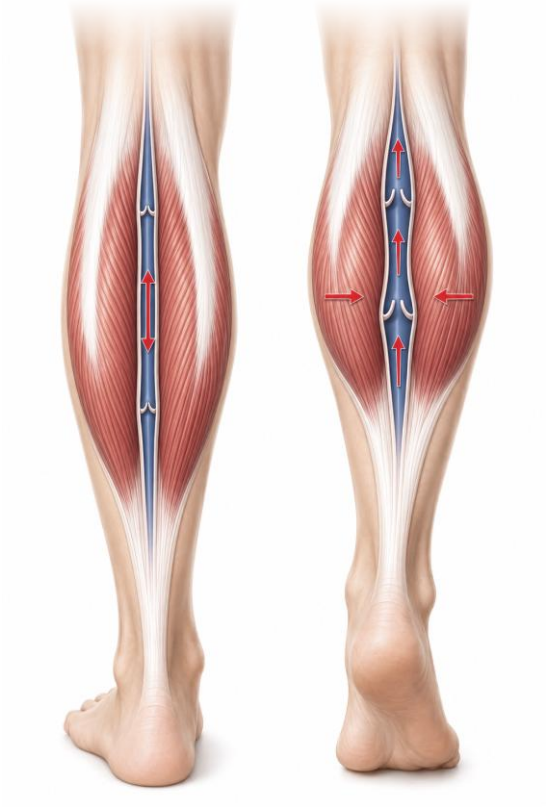
- The venous system is divided into deep and superficial veins, connected by perforating veins;
- Perforating veins direct blood from the superficial veins into the deep system;
- One-way valves help maintain forward flow and prevent reflux;
- Deep veins include the femoral, popliteal, and tibial veins and carry around 85–90% of venous return.

Deep venous system and normal blood flow



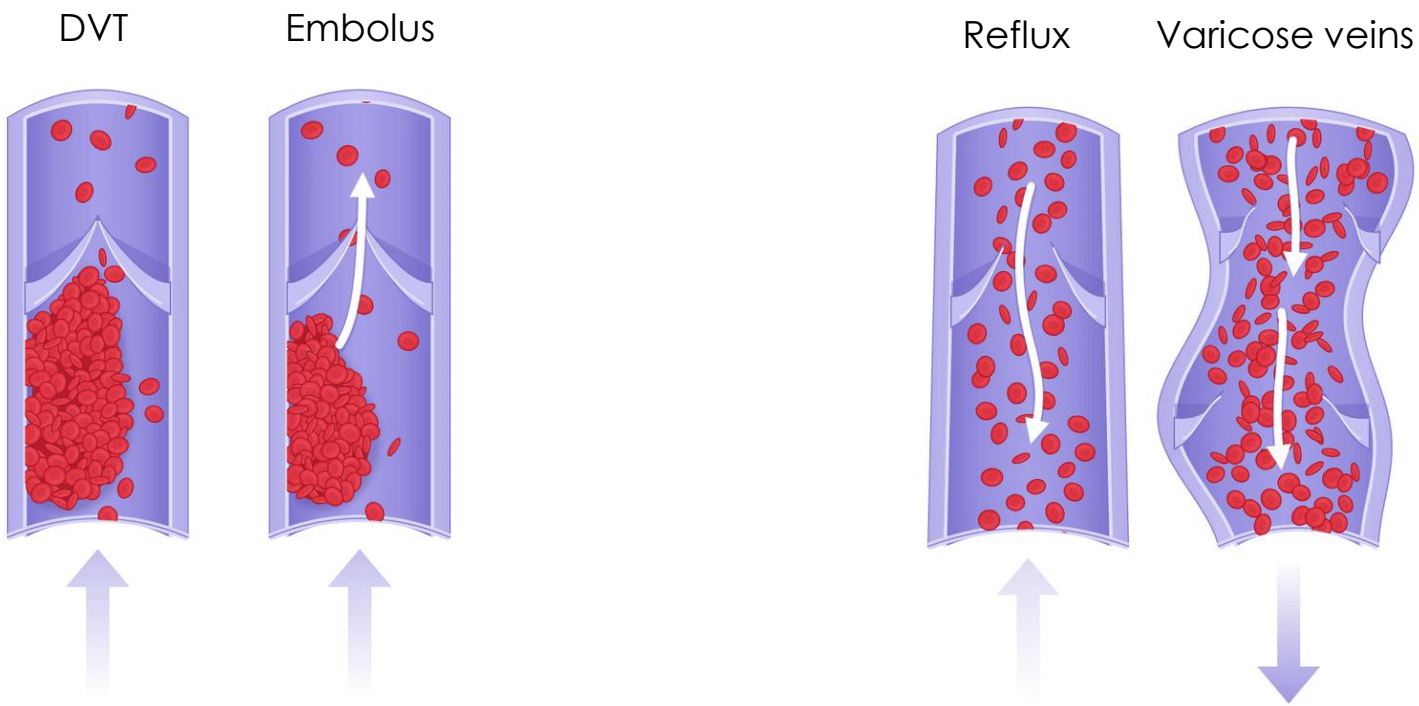
Venous hemodynamics

- Venous flow is highly variable and depends on posture, movement, respiration, and calf muscle activity;
- Resting venous flow is slow and variable: <20 cm/s during breathing, ~21-25 cm/s after Valsalva, and up to ~90 cm/s during active calf muscle pumping;
- In a healthy person standing still, venous pressure at the ankle is around 90 mmHg, and walking lowers it to roughly 20–30 mmHg;
- Blood is pushed upward from the legs by the calf muscle pump, while one-way valves prevent it from flowing backward.



Venous pathologies

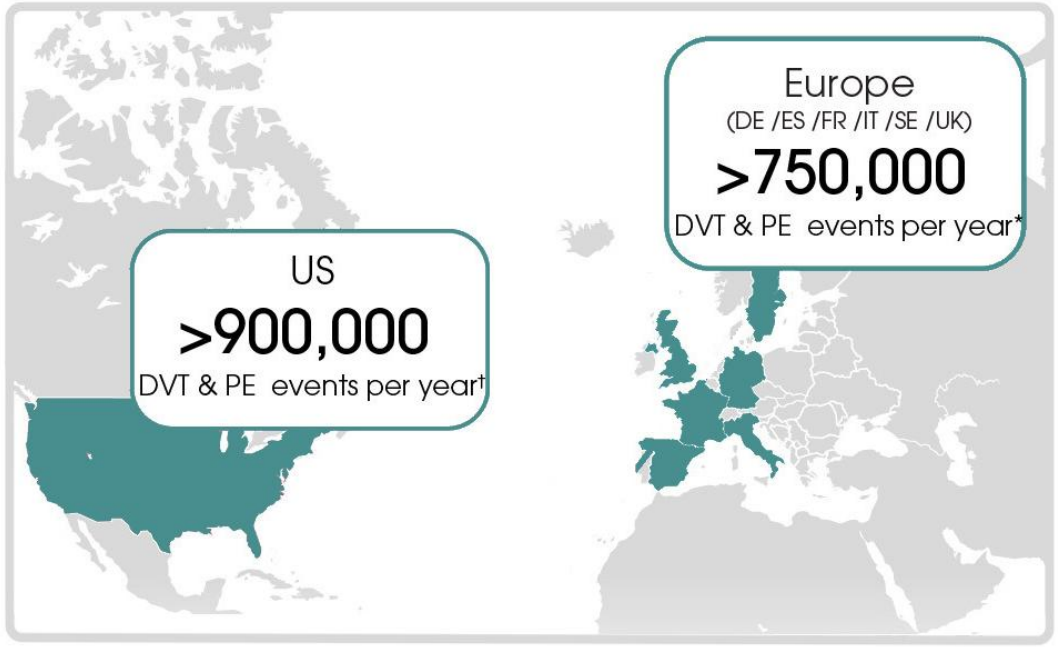
- In deep vein thrombosis (DVT), the formation of a blood clot is understood to be influenced by three key factors: blood flow stasis, vein wall injury, and hypercoagulability;
- In venous insufficiency (CVI), incompetent valves let blood flow backwards, which leads to varicose veins.



Nicholson, M., Chan, N., Bhagirath, V., & Ginsberg, J. (2020). Prevention of venous thromboembolism in 2020 and beyond.

Incidence

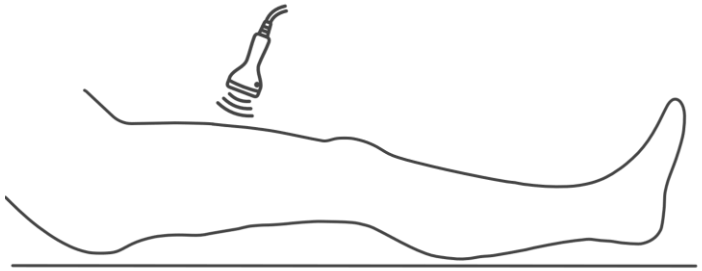
- The incidence is steadily increasing due to an aging population and associated comorbidities such as obesity, heart failure, and cancer;
- Venous thromboembolism is the third leading cause of cardiovascular death worldwide;
- Venous insufficiency is also a frequent consequence of DVT, with 20–50% of patients developing post-thrombotic syndrome.



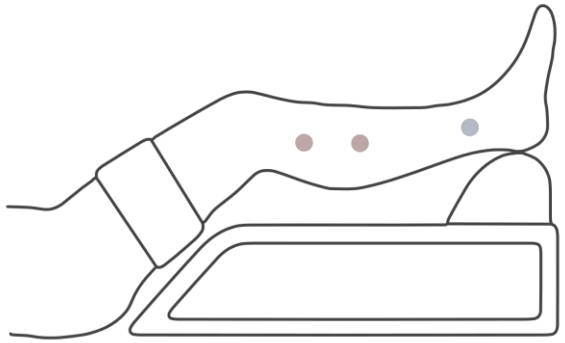
Di Nisio, M., van Es, N., & Büller, H. R. (2016). Deep vein thrombosis and pulmonary embolism. In The Lancet (Vol. 388, Issue 10063, pp. 3060–3073).

Diagnostic methods

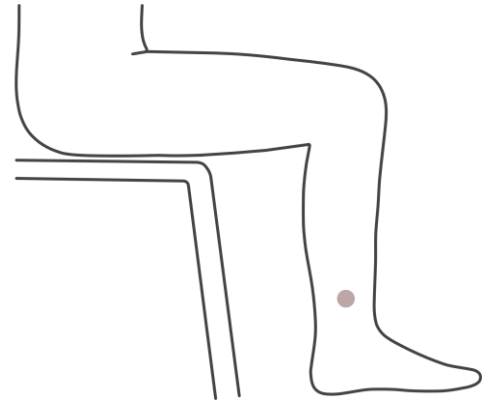
- Duplex ultrasound scanning: the clinical gold standard, using imaging and Doppler to assess venous compressibility and blood flow;
- Venous occlusion plethysmography (VOP): measures limb volume changes during cuff occlusion to assess venous filling and outflow;
- Light reflection rheography (LRR): uses infrared light to track skin blood volume changes during dorsiflexion.



Duplex ultrasound scanning



Venous occlusion plethysmography



Light reflection rheography

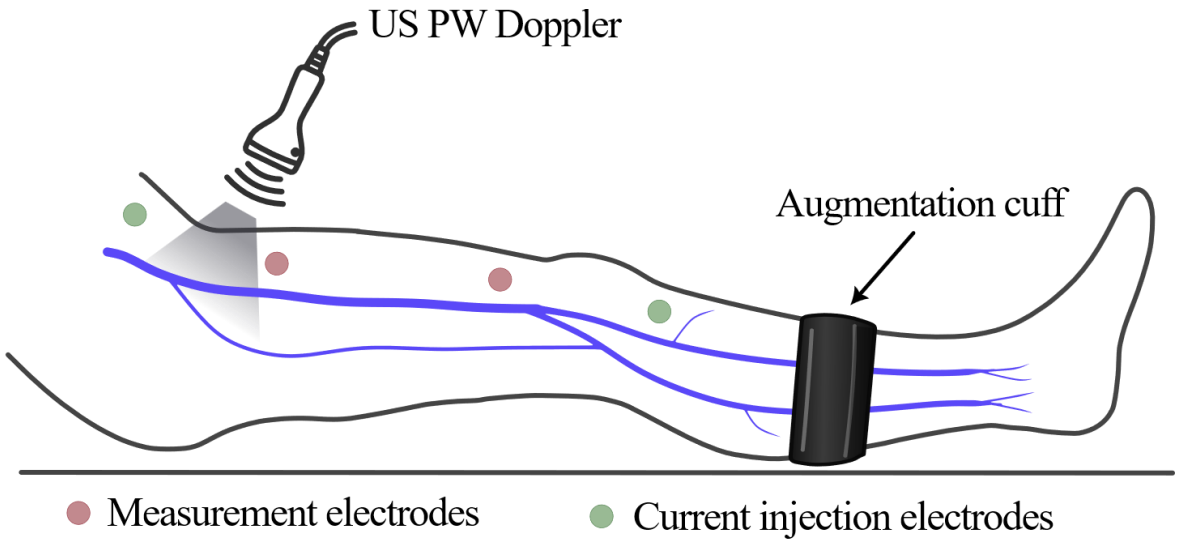
Problem definition

- **Current clinical standard:** Duplex ultrasonography **requires an experienced sonographer**, making it unsuitable for operator-independent screening or long-term monitoring;
- **Alternative methods** such as VOP and LRR exist, but their use remains limited:
  - **VOP** requires **leg elevation** and takes approximately 5 minutes per measurement;
  - **LRR** requires **active patient participation** (e.g., performing calf exercises), and its results are subjective, since the patient's performance may vary or be physically limited.

To address these limitations, we proposed a pilot study of a new method that is faster, does not require continuous operator involvement, and is independent of patient effort.

Study protocol and experimental setup

- The main protocol included baseline breathing followed by controlled augmentation pulses at different pressure levels and pulse widths;
- Three signals were recorded simultaneously:
  1. Pneumatic augmentation pulses were generated and measured using a custom Pulser device;
  2. PW Doppler velocity was recorded from the femoral vein using an ultrasound probe holder;
  3. Bioimpedance was measured from the inner thigh using a four-electrode configuration.

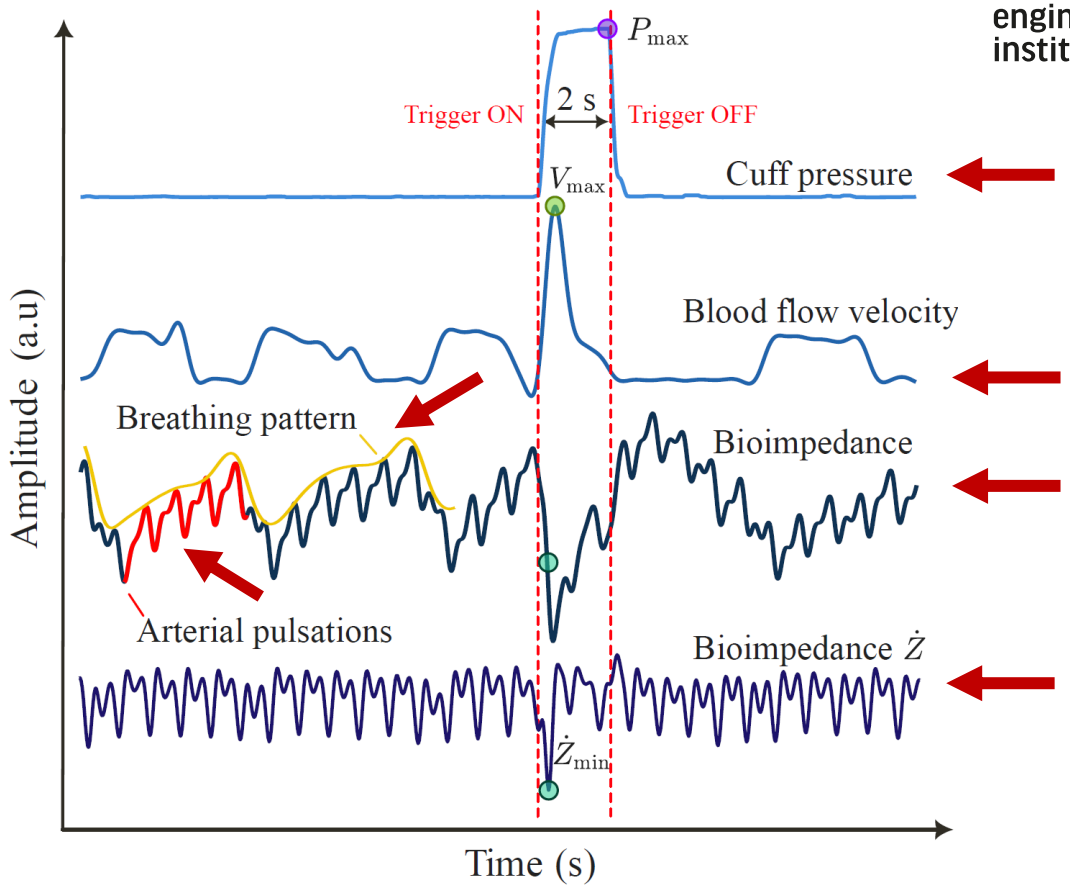


Data and methodology

Data: Nine subjects (2 women) were included in the pilot study.

Methodology:

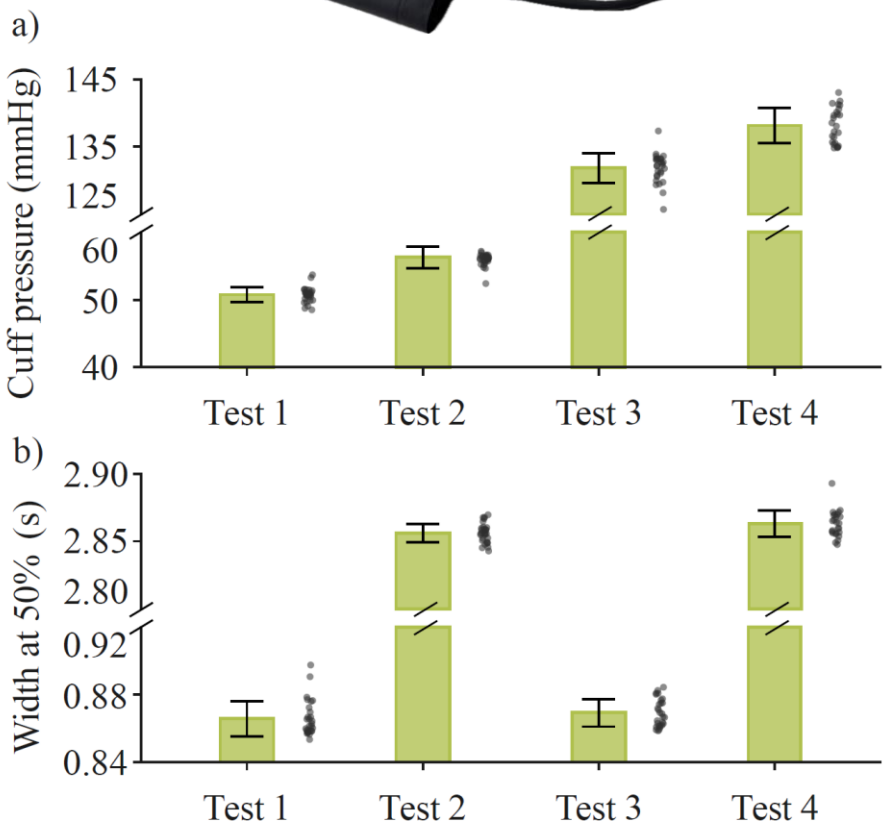
- Three signals were preprocessed separately: cuff pressure, PW Doppler blood flow velocity, and bioimpedance;
- Bioimpedance was high-pass filtered to reduce baseline drift and respiratory components, then smoothed while preserving waveform shape;
- The bioimpedance response was quantified as the maximum falling slope, defined as the minimum of the first derivative $\dot{Z}_{min}$.



Results I: Repeatability of pneumatic pulses

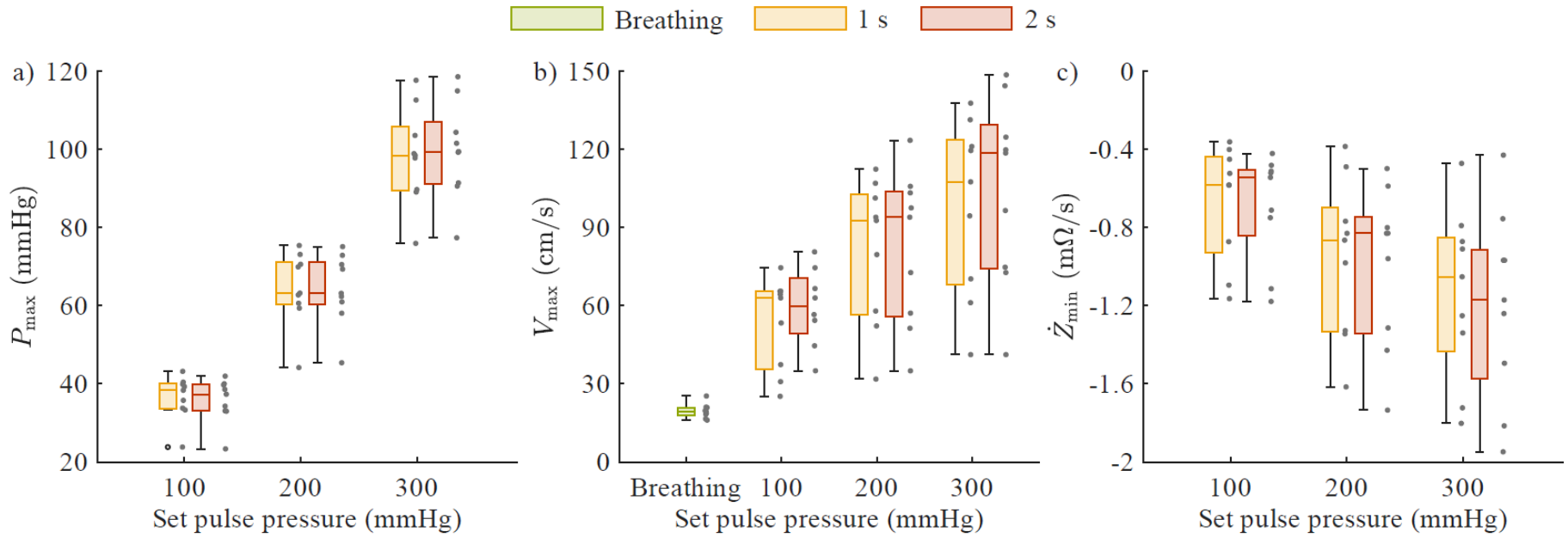
- Repeated measurements under identical conditions showed stable actuator performance;
- Cuff pressure variability was very low: SD ~ ±1.12 to ±2.63 mmHg;
- Pulse-width variability was very small: SD ~ ±0.007 to ±0.011 s;
- The Pulser produced repeatable pneumatic pulses in both magnitude and time.





Results II: Augmented outflow analysis

- Cuff pressure increased consistently with the selected augmentation level;
- Doppler velocity increased from ~19 cm/s at baseline to ~60 cm/s at the lowest and ~110–119 cm/s at the highest augmentation level;
- Bioimpedance response magnitude also increased with pressure, with steeper negative slopes at higher augmentation levels;
- Pulse duration had a smaller effect than pulse pressure.



Conclusions

1. A pneumatic **Pulser device was developed and demonstrated the repeatable generation** of controlled augmentation pulses;

2. Controlled lower-limb **venous augmentation produced pressure-dependent changes in both** PW Doppler femoral vein velocity and bioimpedance-derived response;

3. The **agreement between Doppler and bioimpedance** responses **supports the feasibility of bioimpedance-based detection** of venous outflow augmentation and motivates further development of biosignal-based venous assessment methods.

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