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A Pilot's Work of Breathing Assessment in High Altitude, Masked Environments

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Disclosure Information

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We have no financial relationships to disclose.

We will not discuss off-label use and/or investigational use in our presentation

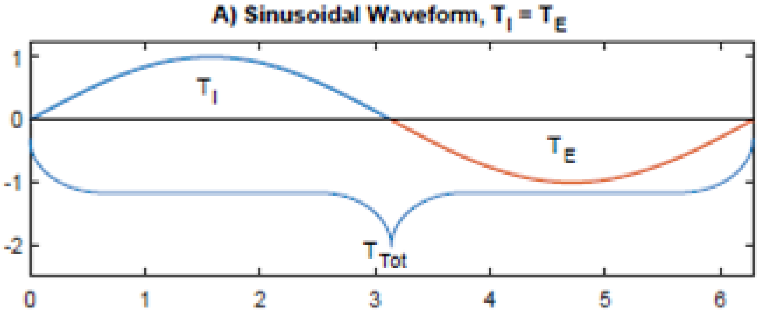
Introduction

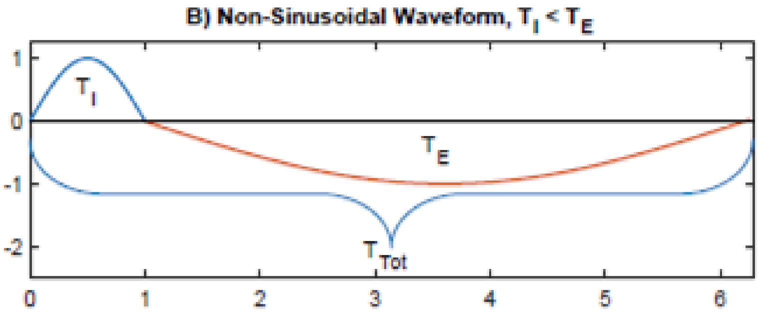
- **Work of Breathing (WoB)** is expenditure by respiratory muscles to maintain appropriate gas exchanges (alveolar ventilation)
- Target Population: Fighter Pilots
  - Operate in extreme environments that require supplemental techniques and equipment
    - Masked breathing
    - Anti-G Straining Maneuvers (AGSM)

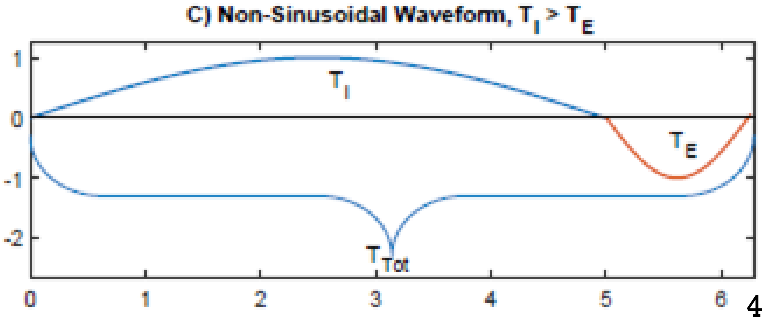
Bottom Line Up Front (BLUF): The way a pilot breathes is unique and WoB should be evaluated based on these conditions.

Waveforms and Definitions

- **Sinusoidal Waveform (A)**
  - Total time for a single breath (T_{Tot}) is broken down into equal lengths of inspiration (T_I) and expiration (T_E)
- **Non-Sinusoidal Waveform (B, C)**
  - $T_I = T_E$
  - $T_I < T_E$ (ex: hyperventilation mechanics)
  - $T_I > T_E$ (ex: AGSM)
- **Period:** one cycle of breath's inspiration and expiration time
- **Breathing Rhythm:** the cadence of Ti and Te used to maintain alveolar ventilation
- **Instantaneous inspired frequency (Hz):** the amount of airflow entering one's lungs when one takes a breath
  - Non-sinusoidal model: simplifies and relates f and T_I by $f = \frac{1}{2} * T_I$ and assumes expiration is passive
- **Breathing Rate (BPM):** the number of breaths taken per minute **($B_R = f$ for sinusoidal waveforms *only*)**







Methods: Model Basis and Generation

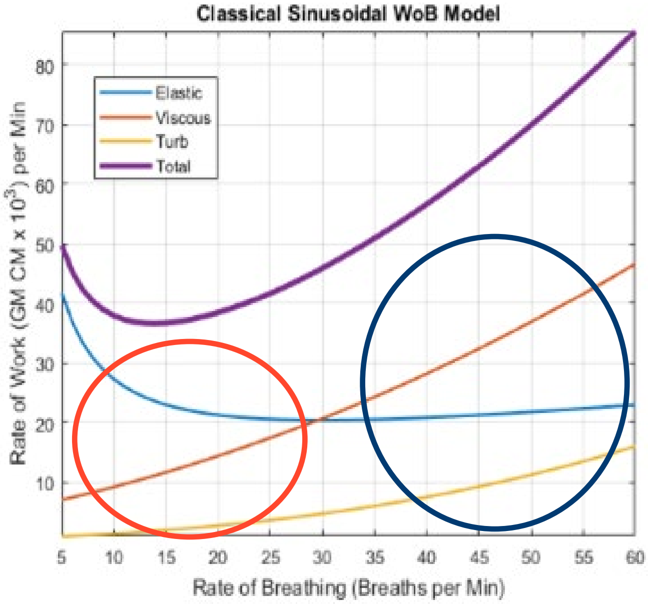
- Flow model vs. pressure volume model
- We expanded the flow model for WoB developed from classical model by Otis et al.

$$W_{Tot} = \frac{1}{2}KV_T^2 + \frac{1}{4}K'\pi^2 f V_T^2 + \frac{2}{3}K''\pi^2 f^2 V_T^3$$

- Non-sinusoidal equation for WoB (Napoli et al.):

$$W_{Tot} = \frac{1}{2}KB_R V_T^2 + \frac{1}{4}K'\pi^2 B_R f V_T^2 + \frac{2}{3}K''\pi^2 B_R f^2 V_T^3$$

- Breathing Rate Ranges
  - Normal breathing rate < 25 BPM (elastic forces dominant)
  - Extreme case: 60 BPM (equal to 1 Hz)
  - AGSM breathing for fighter pilots: up to 4 Hz



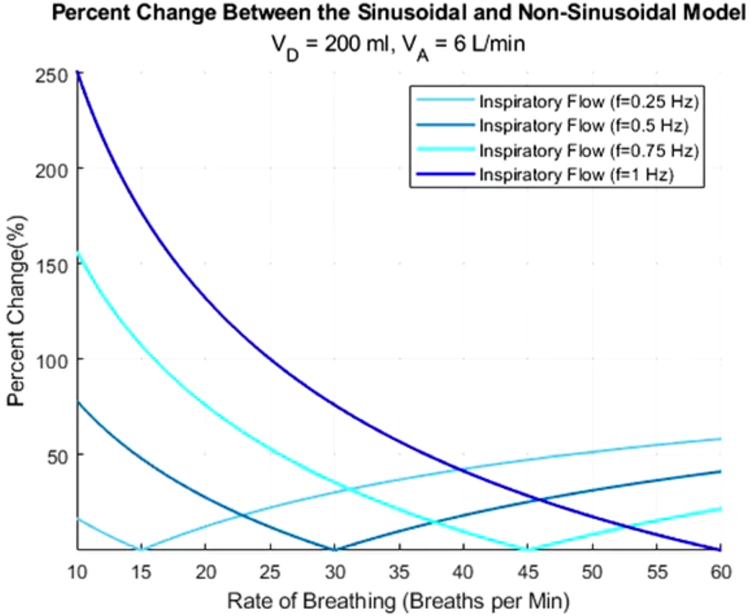
- Napoli, Nicholas J., Victoria R. Rodrigues, and Paul W. Davenport. "Characterizing and Modeling Breathing Dynamics: Flow Rate, Rhythm, Period, and Frequency." *Frontiers in Physiology* (2022): 2305.
- Otis, Arthur B., Wallace O. Fenn, and Hermann Rahn. "Mechanics of breathing in man." *Journal of applied physiology* 2.11 (1950): 592-607.

Research Questions (RQ)

1. RQ1: What is impact of high frequency breathing on the non-sinusoidal WoB compared to the classical model?
2. RQ2: What is the impact of dead space on WoB for fighter pilots?
3. RQ3: Is it possible to connect alveolar ventilation changes to breathing compromise under in-flight conditions?

RQ1: What is the impact of high frequency breathing on the non-sinusoidal WoB compared to the classical model?

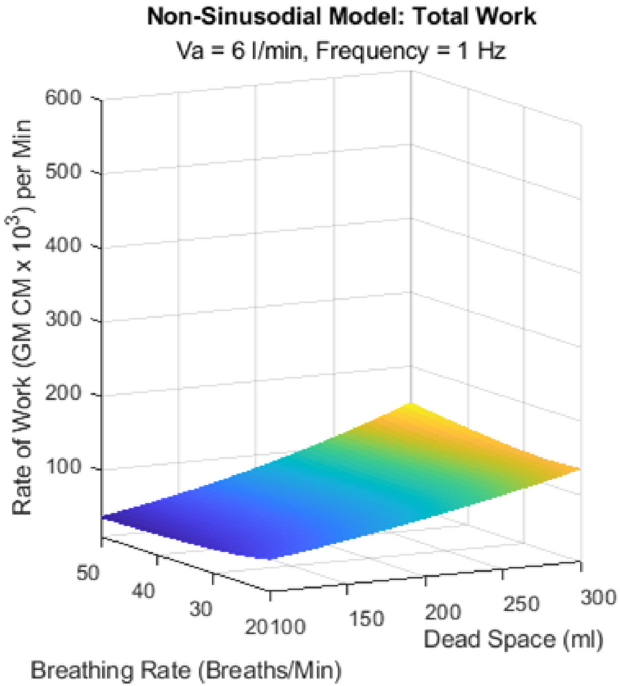
- Why do we see this large deviation?
  - Inspired frequency of breathe due to viscous and turbulent forces overtaking elastic
- Important Consideration-- Context of analysis

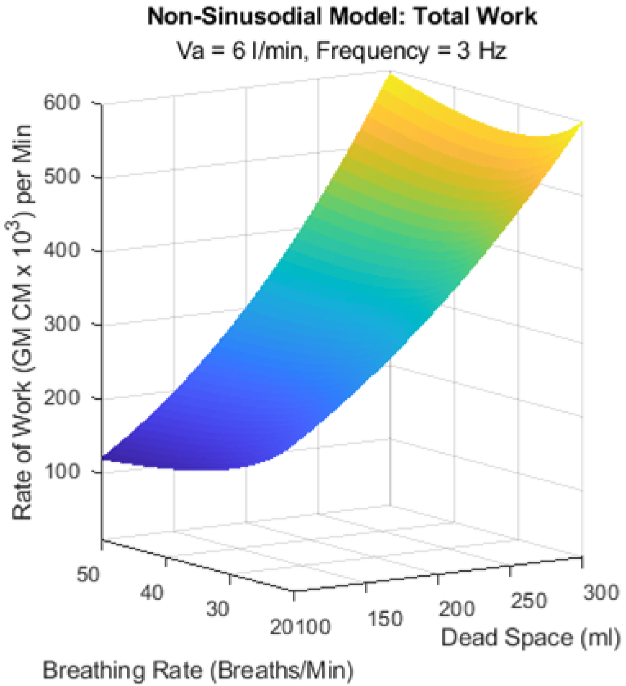


Main takeaway: For high frequency breathing (i.e. pilot AGSM), this model indicates that the classical model drastically underestimates WoB because the viscous and turbulent forces greatly overcome the elastic force.

RQ2: What is the impact of dead space on WoB for fighter pilots?

- **Dead Space:** air that does not participate in the gas exchange
- Mask wear increases dead space
- As we increase the frequency and dead space, the region of optimality drastically changes





Main Takeaway: WoB increases exponentially compared to the classical model as dead space and frequency increases

RQ3: Is it possible to connect alveolar ventilation changes to breathing compromise under in-flight conditions?

- **Alveolar Ventilation** (V_A): the inspired air that travels to the alveoli for gas exchange
- Frequency can alter V_A by the approximation:
  - $f = \frac{1}{2} * T_I$
- VA is the priority for the human body to maintain normal breathing
  - Every change requires a balancing reaction
  - If equilibrium is not met, respiratory compromise can occur

Sinusoidal Model

$$V_A = (V_T - V_D) * B_R$$

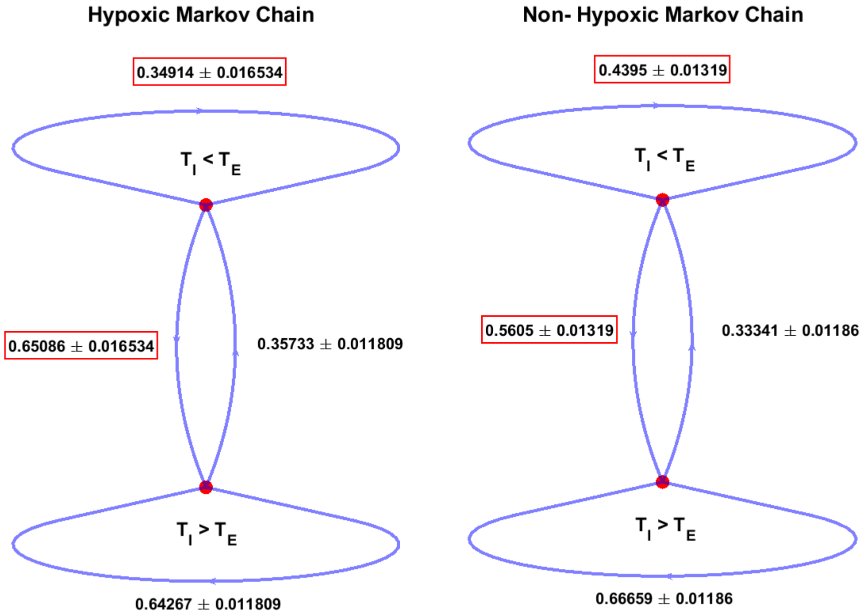
$$= (V_T - V_D) * \frac{1}{T_{Tot}} * 60$$

Non-Sinusoidal Model

$$= (V_T - V_D) * \frac{1}{T_I + T_E} * 60$$

RQ3: Is it possible to connect alveolar ventilation changes to breathing compromise under in-flight conditions?

- **Breathing Compromise** occurs when appropriate gas exchange is not met and the person is unable to return to homeostasis
- Hypothesis: transitions between T_I and T_E may be useful in predicting breathing compromise
- Significant transitions between hypoxic and non-hypoxic cohorts outlined in red $(p < 0.001)$
- Drive to inspire greater when hypoxic



Main Takeaway: Hypoxic and non-hypoxic cohorts demonstrate differences in inspiration and expiration transitions, and may be useful in predicting breathing compromise.

Conclusion

- Main Takeaways
  - Simulated results indicate that the classical model is an extreme underestimation of WoB when measured in unique contexts
  - A pilot's environment and supplemental equipment, including mask wear and high-G maneuvers, impacts pilots' breathing patterns, particularly when using non-sinusoidal modeling
  - Inability to maintain alveolar ventilation can lead to breathing compromise
    - Through analysis of the alveolar ventilation equation, we can better understand breathing compromise.
- Future Work and Limitations
  - This is a model
  - Transition probabilities are not based on the flow model

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Questions?