Effect of face shape on effectiveness of facemask for large population

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Airborne transmission of respiratory diseases remains a pressing global health concern, with face masks playing a critical role in reducing transmission risk. However, mask effectiveness depends on complex interactions between facial morphology, mask design, and respiratory dynamics. This dissertation develops reduced-order physics-based and machine-learning models to systematically evaluate mask performance across diverse facial geometries and respiratory conditions, with an emphasis on leakage dynamics and their epidemiological implications.

The first component of this research introduces a semi-analytical flow network model, grounded in the Kármán–Pohlhausen momentum integral technique, to quantify airflow leakage in large populations. By representing the mask–face interface as a network of variable-height porous channels, this reduced-order framework captures both inward and outward protection characteristics during breathing. Results highlight the nose region as a critical leakage site, particularly in the absence of a nose clip, where high-velocity jets can bypass filtration. Subtle variations in facial features, such as the zygomatic arch and chin shape, were shown to significantly alter leakage pathways, underscoring the importance of demographic diversity in mask evaluation. Furthermore, this work clarifies the dual role of nose clips: while they enhance sealing in well-fitted masks, they can also redirect leakage flows in imperfect fits, with complex implications for population-scale mask effectiveness.

Building upon this foundation, the second component extends the flow network model to dynamic speech scenarios, where facial deformations alter mask performance in time. Talking generates transient jets with velocities 1.5–5.6× higher than quiet breathing, leading to amplified leakage patterns. A physics-informed “speech aerodynamics dictionary” was constructed by analyzing phoneme-driven articulations across diverse facial morphologies, revealing that certain sounds disproportionately compromise mask efficacy. This study demonstrates that traditional static mask testing underestimates real-world leakage by a factor of 3–5, pointing to critical limitations of one-size-fits-all designs and static testing standards.

Collectively, these contributions establish a unified modeling framework that links facial morphology, mask design, and respiratory activities to leakage dynamics. The results provide mechanistic insights into how masks function under realistic conditions, highlight the influence of nose clips and facial features on protection levels, and quantify the underappreciated role of speech in airborne transmission. As a complementary study, Chapter 4 applies similar fluid-structure interaction principles to flexible fiber

sedimentation, demonstrating the broader applicability of deformation-driven flow modeling beyond respiratory protection. Beyond advancing the physics of respiratory flows, this work delivers computationally efficient tools with direct implications for mask design, public health guidelines, and pandemic preparedness strategies.