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Characterising applied forces during positive pressure ventilation: a randomised cross-over simulation study

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ABSTRACT

Objective To characterise applied force on the face and head during simulated mask ventilation with varying mask, device and expertise level.
Design Randomised cross-over simulation study.
Setting A quiet, empty room in the children's hospital.
Participants Neonatal healthcare providers, categorised as novices and experts in positive pressure ventilation (PPV).
Interventions PPV for 2 min each in a 2×2 within-subjects design with two masks (round and anatomic) and two ventilation devices (T-piece and self-inflating bag (SIB)).
Main outcome measures Applied force (Newton (N)) measured under the head and at four locations on the manikin's face (nasal bridge, mentum, left and right zygomatic arches) and symmetry of force applied around the mask rim.
Results For the 51 participants, force applied to the head was greater with the SIB than the T-piece (mean (SD): 16.03 (6.96) N vs 14.31 (5.16) N) and greater with the anatomic mask than the round mask (mean (SD): 16.07 (6.80) N vs 14.26 (5.35) N). Underhead force decreased over the duration of PPV for all conditions. Force measured on the face was greatest at the left zygomatic arch (median (IQR): 0.97 (0.70–1.43) N) and least at the mentum (median (IQR): 0.44 (0.28–0.61) N). Overall, experts applied more equal force around the mask rim compared with novices (median (IQR): 0.46 (0.26–0.79) N vs 0.65 (0.24–1.18) N, p<0.001).
Conclusion We characterised an initial dataset of applied forces on the face and head during simulated PPV and described differences in force when considering mask type, device type and expertise.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The effectiveness of face mask ventilation is dependent on proper technique. Mask leak and airway obstruction are common issues causing ineffective ventilation. Actions taken to correct leak can result in airway obstruction.

WHAT THIS STUDY ADDS

⇒ During mask ventilation of a manikin, force applied to the head varies based on mask and device type and consistently decreases over the duration of PPV. Increased force exerted on the head is not related to unbalanced force symmetry exerted on the face. Overall, experts apply more equal force around the rim of the mask than novices. In some cases, increased force on one side of the manikin's face corresponded to the hand holding the face mask.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study is the first to characterise applied forces on the face and head jointly during simulated ventilation. These data have potential to serve as additional metrics for evaluating proper technique while learning mask ventilation.

INTRODUCTION

Positive pressure ventilation (PPV) is the most critical step in neonatal resuscitation.[1 2] Effective PPV requires proper mask placement and technique to minimise mask leak, while avoiding obstruction or injury from excessive force applied to the mask.[3] Previous studies have measured leak and obstruction to evaluate ventilation success between different mask and device types but did not consider applied forces.[4–7] Kuypers *et al*[8] measured total force applied to the face mask during PPV in preterm newborns and found an association between applied forces and risk of apnea and bradycardia. Van Vonderen *et al*[9] investigated compressive forces applied to a manikin's head during simulated PPV but did not evaluate differences by mask type or examine the distribution of forces at the face–mask interface.

Understanding applied forces on the face and head during PPV could support training by providing quantitative feedback to improve technique. We previously validated a benchtop system for measuring the applied forces during simulated PPV.[10] The present study characterises applied forces on the manikin's face and head during simulated PPV for different devices, masks, and healthcare provider (HCP) experience levels.

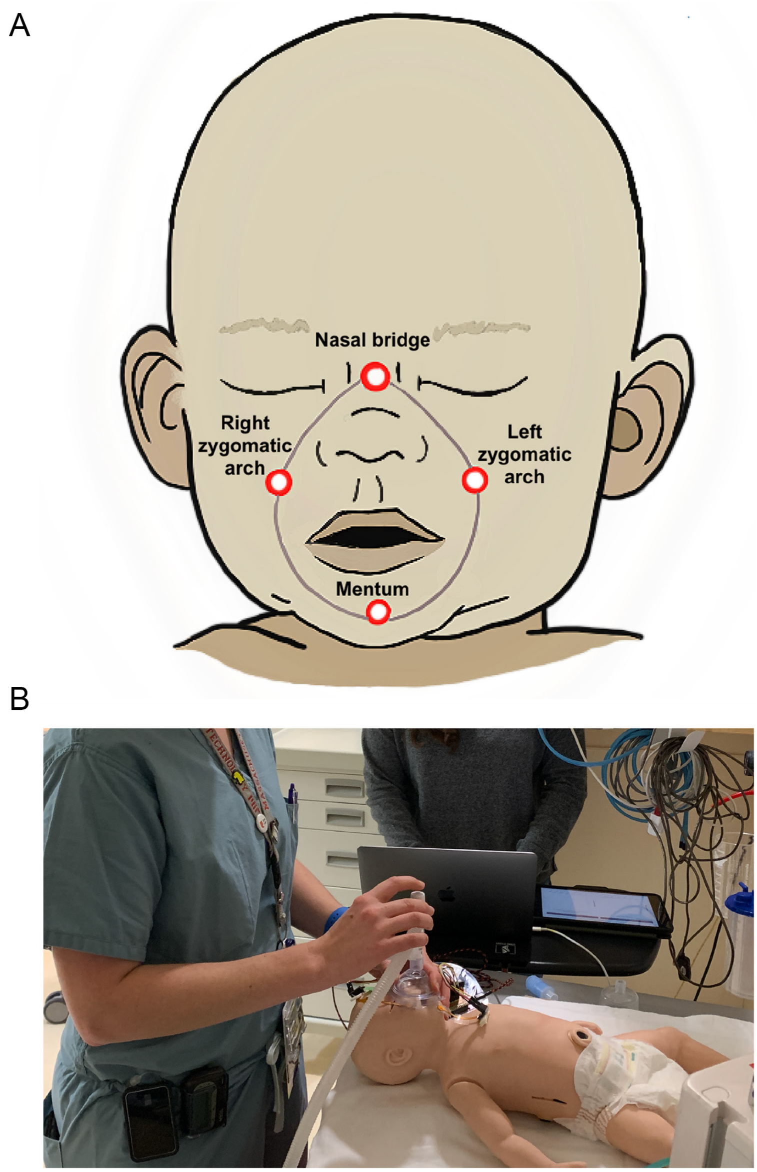

Figure 1 (A) Diagram of the SingleTact sensor configuration on the manikin's face.[10] (B) Participant ventilating the manikin with force sensor system.

METHODS

Participants (n=53) were recruited from C.S. Mott Children's Hospital at the University of Michigan (November 2022 to January 2023). HCPs with 2 years or less of experience administering neonatal PPV were categorised as novices (n=25), while those with greater than 2 years of experience were categorised as experts (n=28). All subjects previously completed American Academy of Pediatrics Neonatal Resuscitation Program (NRP) training. Prior to beginning the simulation, a survey was administered to collect information about PPV experience. Participants completed four 2 min trials of simulated PPV, with 1 min of rest between each trial, using a SimNewB full-term manikin (Laerdal Medical, Stavanger, Norway) in a 2×2 randomised Latin square design. Participants were instructed to perform PPV following NRP guidelines (peak pressure 25 cmH_2O, positive end expiratory pressure (PEEP) 5 cmH_2O, rate 40–60 breaths per minute). Participants were informed that we were investigating applied forces during PPV. Device types included a Neopuff T-piece resuscitator (Fisher Paykel, Auckland, New Zealand) and a 500 mL self-inflating bag (SIB) with a PEEP valve and manometer (Mercury Medical, Clearwater, Florida, USA). Mask types included an infant anatomic inflated-rim mask (Medline, Northfield, Illinois, USA) and a 60 mm round membrane-rim mask (Fisher Paykel, Auckland, New Zealand). During PPV, participants could see the manometer but could not see force measurements and did not receive feedback from the investigator. Simulations were performed in a quiet room within the hospital on a Resuscitation Quality Improvement (RQI) cart (RQI Partners, Dallas, Texas, USA).

Four pre-calibrated ultrathin microforce sensors (SingleTact, PPS UK, Glasgow, UK) were applied on the manikin's face at the nasal bridge, mentum and the left and right zygomatic arches (figure 1). Force (Newton (N); 1 N=102 gram-force) under the head was measured with a modified

Table 1 Participant demographic information

	Novices	Experts
N	25	28
Gender		
Female	21	23
Male	4	5
Age (mean (SD))	28.9 (2.8)	41.3 (9.7)
PPV experience		
<1 year	13	0
1–2 years	12	0
3–4 years	0	8
5–6 years	0	3
6+ years	0	17
Hand used for mask hold		
Right	3	5
Left	22	23

PPV, positive pressure ventilation.

load cell (SparkFun Electronics, Niwot, Colorado, USA) concealed from view with a blanket. Forces on the face and underhead (UH) were continuously measured at 20Hz using a microcontroller and custom data collection script. Initial values from each force sensor at resting state were recorded for each trial and were subtracted from the time series such that all sensors had a zero datum when unloaded. A wireless respiratory function monitor (Monivent, Gothenburg, Sweden) was placed between the mask and the PPV device; however, we encountered unanticipated technical difficulty acquiring reliable data during the simulations and these data are not reported. Data from one novice subject and one expert subject were censored prior to analysis due to missing data from disconnected force sensors.

A linear mixed effects (LME) model was fit to characterise the forces measured under the manikin's head for each condition over time. A repeated measures analysis of variance (ANOVA) was fit to characterise the relationship of mask type, device type, experience level and force sensor location on the force measured at the face–mask interface. An additional metric, asymmetry index, was calculated as the square root of the sum of squares of the face force sensor differences. The asymmetry index describes how evenly force is distributed around the mask rim, with zero indicating perfectly equal force distribution. A second repeated measures ANOVA was fit to characterise the relationship of mask type, device type and experience level on the asymmetry index. A Pearson correlation was used to assess linearity between the UH force and asymmetry index. Data are presented as mean (SD) for normal distributions and median (IQR) for skewed distributions. Dependent t-tests were used to compare results for within-subjects factors (mask and device type), and independent t-tests were used to compare result for the between-subjects factor (expertise). Statistical analyses were performed with MATLAB 2022 edition (MathWorks, Natick, Massachusetts, USA).

Patient and public involvement statement

Patients or the public were not involved in the design, conduct, reporting or dissemination of our research.

RESULTS

We enrolled 26 paediatric residents, 10 neonatology attendings, 4 neonatology fellows, 8 neonatal advanced practice professionals and 5 respiratory therapists, categorised into novices and experts (table 1). UH force varied by mask and device type (figure 2). Forces were greater when using the SIB compared with the T-piece resuscitator (mean (SD): 16.03 (6.96) N vs 14.31 (5.16) N, p=0.002) and greater when using the anatomic mask compared with the round mask (mean (SD): 16.07 (6.80) N vs 14.26 (5.35) N, p=0.005). The greatest mean UH force was observed for the SIB with anatomic mask (17.30 (7.96) N). Experts and novices applied the least mean force with the T-piece with round mask (12.99 (4.47) N and 14.65 (5.76) N, respectively). The LME model illustrates that, on average, UH force decreases over the duration of each PPV trial (−0.032 N/s, p<0.0001) for all conditions, with small differences in slope depending on condition and expertise. This primary effect is equivalent to a 3.84N decrease in UH force over the 2 min trial.

A logarithmic transformation was applied to face force sensor data prior to statistical analysis. Mask type and device type had no effect on force measured at each face sensor location. However, forces differed depending on HCP experience level and location of the sensor on the manikin's face (figure 3). Although novices applied a greater force across all sensors on the face compared with experts (median (IQR): 0.75 (0.48–1.09) N vs 0.74 (0.48–1.06) N, p<0.001), the effect was negligible (Cohen's d=0.05). The greatest force was applied at the left zygomatic arch (median (IQR): 0.97 (0.70–1.43) N) and the least force was applied at the mentum (median (IQR): 0.44 (0.25–0.61) N). When comparing handedness to forces applied at each face sensor location, a relationship emerged that corresponds to higher force on the side of the mask-holding hand. Individuals who held the mask with their right hand (n=8) had larger applied force at the right zygomatic arch than individuals who held the mask with their left hand (median (IQR): 1.13 (0.75–1.50) N vs 0.86 (0.68–1.13) N, p=0.028). The ANOVA model did not support an effect of mask or device type on the asymmetry index. However, novices had a significantly higher asymmetry index than experts (median (IQR): 0.65 (0.24–1.18) N vs 0.46 (0.26–0.79) N, p<0.001), indicating experts applied force more symmetrically (figure 4). No linear relationship was observed between the asymmetry index and UH force (r=0.04, p=0.55).

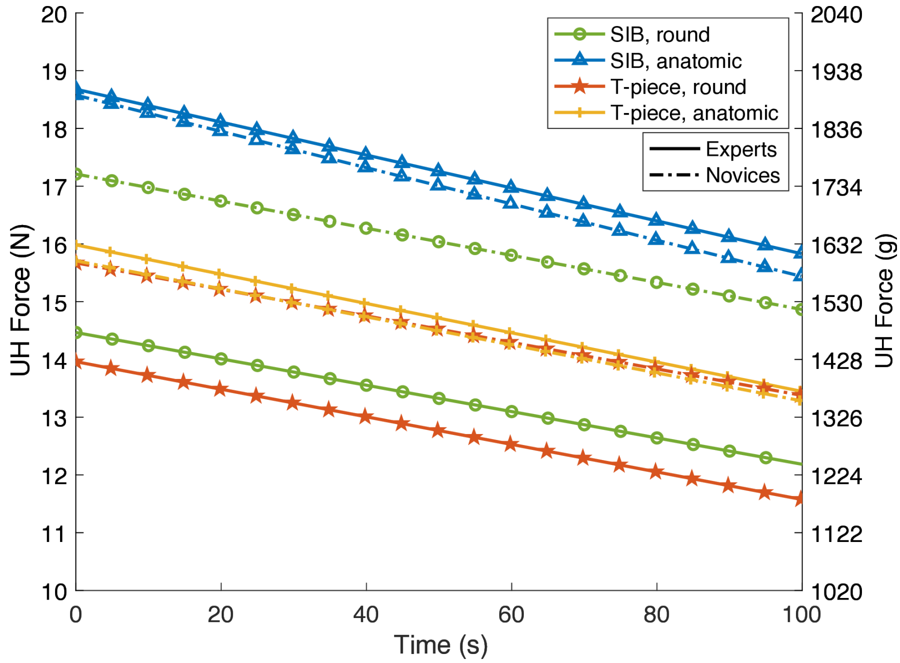

Figure 2 Prediction lines from the linear mixed effects model. Each line represents the predicted underhead (UH) force over time for a given condition and experience level. The left-side axis displays the values in Newton, and the right-side axis displays the values in the gram equivalent. SIB, self-inflating bag.

DISCUSSION

The objectives of this study were to characterise applied forces on the face and head during simulated PPV and assess the effects of mask type, device type and experience on applied forces. We found that mean UH force was higher when using the SIB and anatomic mask and applied force decreased over the time of the trial. In addition, we found that forces measured on the manikin's face were applied asymmetrically, with the greatest force applied to the zygomatic arch on the operator's hand-holding side and the lowest force applied to the mentum. Asymmetry was related to experience, as novice resuscitators applied more asymmetric force compared with expert resuscitators.

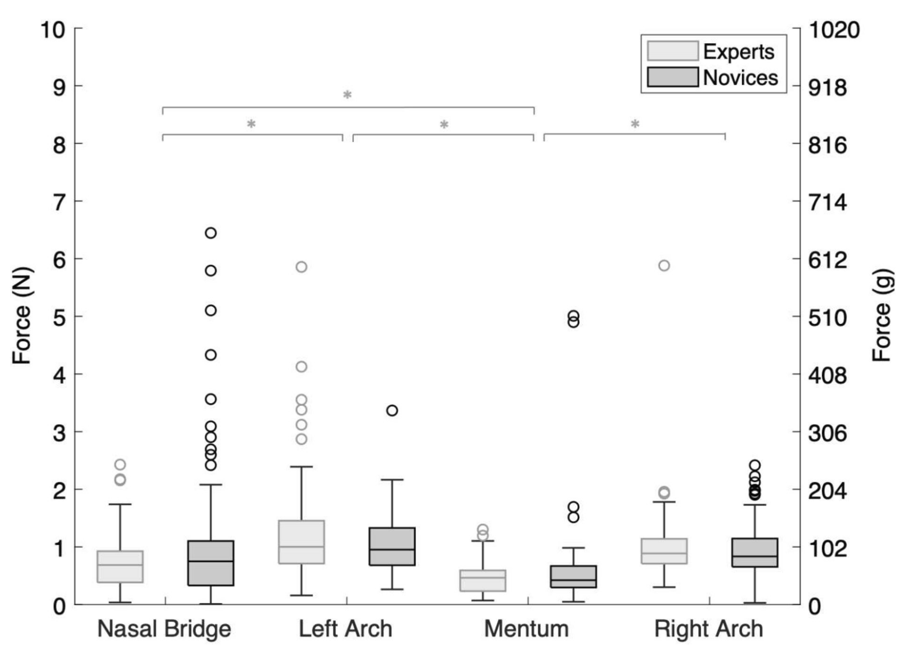

Figure 3 Average force measured at each sensor location on the manikin's face for novices and experts. This plot displays 790 data points, representing four measurements (one for each face force sensor) per person per condition. 26 data points were removed due to disconnection or saturation of the sensor. A negligible effect size (Cohen's d=0.05) was found between experts and novices. The left-side axis displays the values in Newton, and the right-side axis displays the values in the gram equivalent. Asterisk indicates significance between the given sensor locations.

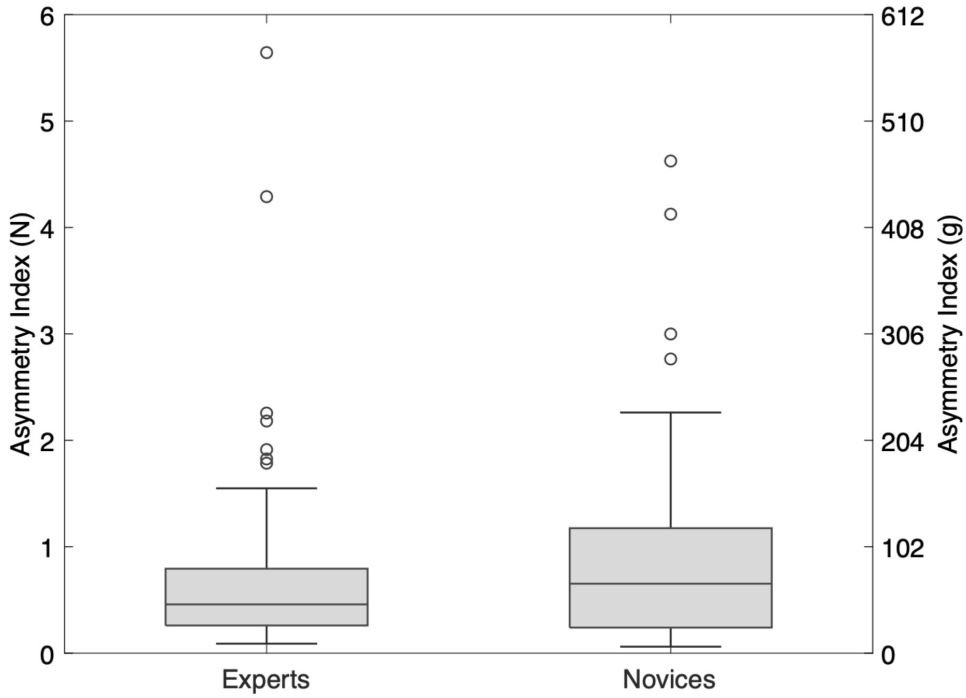

Figure 4 Asymmetry index for experts and novices. Values closer to zero indicate more even force distribution around the face mask rim. This plot displays 204 data points, representing one point per person per condition. The left-side axis displays the values in Newton, and the right-side axis displays the values in the gram equivalent.

Controlling for mask type and experience, mean UH force was lower when clinicians used the T-piece compared with the SIB. We postulate this force decrease may be attributed to the more strenuous posture required when using the SIB. The vertical alignment of the T-piece with the mask, neutral posture and smaller motions required to use a T-piece could result in lower force applied to the manikin's head. Our results differ from van Vonderen *et al*, who reported a trend towards less UH force applied with a T-piece (2205 (932) g) compared with an SIB (1989 (925) g) but found no statistically significant difference between devices.[9] When comparing the force applied by participants in the present study with those in van Vonderen *et al*, we found a similar absolute difference between devices and a similar distribution of data. Overall, participants in the present study used slightly less force with both devices compared with participants in van Vonderen *et al*. This outcome may reflect that participants in this study were informed that applied force was being measured, while those in van Vonderen *et al*'s study were aware that leak was being measured but not force. Given the similarity in the effect size and distribution between studies, we suggest that the larger sample size in the present study allowed us to identify a statistically significant difference between devices that could not be detected by van Vonderen *et al*.

For further context, we converted the applied force to pressure (mm Hg), by dividing the measured force (N) by the sensor surface area (face sensors: 5.03cm^2, occiput contact area with UH sensor: 15.90 cm^2) and compared it to the commonly referenced threshold (32 mm Hg) for preventing soft tissue injury in adults and older children.[11] We found that the pressures measured on the manikin's face were much smaller than this threshold (6.56–14.46 mm Hg), while UH pressure exerted with either device (67.27–81.61 mm Hg) exceeded it. Given the lower mean arterial pressure in newborns, the threshold likely underestimates the potential for soft tissue injury in the neonatal population. This raises concern that if the UH pressures exerted during training sessions with a manikin were sustained during actual resuscitations, they could lead to injury. This potential for injury emphasises the need to ensure that the fidelity of training devices, where learners acquire and practice skills, reflects the actual clinical environment. If technical features including the quality of the simulated skin where it contacts the mask, the structure of the manikin's airway and the compliance of simulated tissues are not realistic, learners may develop dangerous habits in the training environment that are translated to the clinical environment.[12–14] Furthermore, these findings support the recommendation to use a soft mattress below the newborn's head during PPV to distribute forces and minimise the risk for tissue injury.[15]

Our results showed that clinicians applied less force when using the round mask compared with the anatomic mask. This reduction in UH force could arise from the mask design or holding method. The round mask uses a thin, membrane rim to create a seal while the anatomic mask uses an inflated rim. Participants held the round mask by grasping the stem and applying force to the connector positioned between the PPV device and mask.[4] In contrast, the one hand C-E hold was used with the anatomic mask, requiring the operator to apply force directly to the rim of the face mask.[16] This technique causes increased surface contact between the mask-holding hand and the manikin's face. The reduced force with the round face mask raises the question if there was *enough* force to secure the mask to the manikin's face, avoid leak and deliver sufficient tidal volume. Although we intended to measure peak inspiratory pressure and leak around the mask, we were unable to reliably acquire respiratory function data and cannot address this question. Observing the relationship between applied force, mask leak and tidal volume in future studies will provide more information about the forces required to achieve effective ventilation.

Average UH force decreased over the duration of PPV across all conditions, though the magnitude varied slightly depending on condition and expertise. This outcome could be a result of accumulating fatigue over the four 2 min trial periods. Alternatively, participants may have applied a large force when beginning ventilation and decreased the force once they perceived they were achieving the desired peak pressure and chest movement. Measuring clinician muscular activity, applied forces, fatigue and ventilation metrics over time during simulated PPV in future studies could provide additional data to address these hypotheses.

When comparing forces at each face sensor location (figure 3), we observed that force was unevenly applied around the mask rim. The greatest forces were observed at the zygomatic arch corresponding to the mask holding hand. In addition, novices applied more asymmetric force around the mask rim than experts. The lack of correlation between UH force and the asymmetry index indicates that asymmetric force distribution on the face is not a direct result of insufficient or excessive force applied to the head and may occur at both low and high applied forces. These findings emphasise the importance of learning good mask placement during PPV training. Real-time feedback showing trainees how forces are applied on the manikin's face during training sessions could be a useful adjunct to improve the acquisition of PPV skills.

The use of a manikin in this study introduces some limitations in our ability to translate results to newborn infants. Although a commercially available high-fidelity manikin was used, the mechanical properties of the manikin's head and skin may differ from an infant, which could result in discrepancies between the exact measurements reported here and the applied force in a clinical setting. In addition, data collection occurred in a quiet space which differs from the typical setting in which PPV is performed. Although effort was taken to minimise any interference caused by the face force sensors, they could have caused slight deviances in a clinician's ventilation strategy. Finally, force sensors on the manikin's face were placed at four fixed locations, limiting our ability to capture all contact points at the patient interface. Measuring all contact points, including forces applied to lift the jaw, could provide additional information about mask placement and ventilation strategy. Despite these limitations, we believe these data are valuable because they reflect the forces applied by clinicians when using the same manikins used to acquire and practice clinical skills.

In summary, we found that the UH force was greater with the SIB and the anatomic mask, applied force decreased over the duration of PPV and forces were applied asymmetrically to the manikin's face. Our results provide an initial dataset of applied forces at the neonatal patient's face–mask interface and extend previous work that investigated total force applied to the mask[8] and compressive force applied to the head with different device types.[9] These data provide insight into the relationships between device design, expertise and applied forces during PPV. Future studies will examine applied forces in conjunction with measures of posture, fatigue, muscle activation and ventilation metrics to further contextualise a relationship between device design, human factors and effective PPV.

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Contributors All authors have actively contributed. JH conceptualized and designed the study, collected and analyzed data, wrote the first draft of the manuscript, and reviewed and revised the manuscript. GW and LS conceptualized and designed the study, supervised the project, and reviewed and revised the manuscript. All authors approved the final manuscript and accept full responsibility for the work.

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Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by University of Michigan institutional review board (HUM #00211437). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data are available upon request.

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