Wearable positive end-expiratory pressure valve improves exercise performance

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ABSTRACT
We tested a PEEP (4.2 cmH2O) mouthpiece (PMP) on maximal cycling performance in healthy adults. Experiment-1, PMP vs. non-PMP mouthpiece (CON) [n = 9 (5♂), Age = 30 ± 2 yr]; Experiment-2, PMP vs. no mouthpiece (NMP) [n = 10 (7♂), Age = 27 ± 1 yr]. At timepoint 1 in both experiments (mouthpiece condition randomized) subjects performed graded cycling testing (GXT) (Corival® cycle ergometer) to determine VO2peak (ml/kg/min−1), O2pulse (ml/kg/min−1), GXT endurance time (GXT-TTE), and VO2@ventilatory-threshold (VO2@VT). At timepoint 2 72 h later, subjects completed a ventilatory-threshold-endurance-ride (VTER) timed to exhaustion at VO2@VT power [W]. One week later at timepoints 3 and 4 (time-of-day controlled), subjects repeated testing protocols under the alternate mouthpiece condition. Selected results (paired T-test, p < 0.05): Experiment 1 PMP vs. CON, respectively: VO2peak = 45.2 ± 2.4 vs. 42.4 ± 2.3 p < 0.05; VO2@VT = 33.7 ± 2.0 vs. 32.3 ± 1.6; GXT-TTE = 521.7 ± 73.4 vs. 495.3 ± 72.8 (p < 0.05); VTER = 846.2 ± 166.0 vs. 743.1 ± 124.7; O2pulse = 24.5 ± 1.4 vs. 23.1 ± 1.3 (p < 0.05). Experiment 2 PMP vs. NMP, respectively: VO2peak = 43.3 ± 1.6 vs. 47.1 ± 1.6 (p < 0.05); VO2@VT = 31.1 ± 1.2 vs. 29.1 ± 1.3 (p < 0.05); GXT-TTE = 511.7 ± 49.6 vs. 486.4 ± 49.6 (p < 0.05); VTER 872.4 ± 134.0 vs. 792.9 ± 122.4; O2pulse = 24.1 ± 0.9 vs. 23.4 ± 0.9 (p < 0.05). Results demonstrate that the PMP conferred a significant performance benefit to cyclists completing high intensity cycling exercise.

Introduction
PEEP is defined as the positive pressure above atmospheric that remains in the pulmonary airways after exhalation. PEEP has been widely applied in clinical populations, commonly accompanied by mechanical ventilation.1-4 Three to five cmH2O PEEP increases transpulmonary pressure and alveolar recruitment in patients with a variety of pulmonary complications, including chronic obstructive pulmonary disease (COPD), acute respiratory distress syndrome, and severe respiratory failure.1,5 Within these groups, PEEP has been shown to reduce pulmonary shunting,5 improve arterial oxygenation (PaO2) concomitant with increased functional residual capacity,6,7 and reduce the work of breathing.3 Increasing PEEP, combined with increasing the fraction of O2 inspired, is a primary method applied in mechanically-ventilated patients to increase oxygen saturation and PaO2 levels.

While the use of PEEP in pulmonary medicine is well-accepted, the possibility of an exercise benefit for healthy and athletic men and women has not been explored until now. The light-weight, wearable PMP tested in this present study employs the user’s own inspiratory force to generate mild (4.2 cmH2O) PEEP with almost no restriction on inspiration. Thus, the PMP can be comfortably used during exercise training and during competition, and could in theory improve PaO2. An increase in PaO2 in athletes has long been known to improve exercise capacity.9,10 On this basis we hypothesized that wearing the PMP would enhance endurance performance. Therefore, we designed two similar experiments to answer a singular question: Does wearing a PMP confer an exercise performance advantage to healthy, physically active men and women performing high-intensity cycling exercise?
Abbreviations:

| Abbreviation | Description |
|--------------|-------------|
| BP           | Blood pressure (mmHg) |
| BMI          | Body Mass Index |
| CON          | Control Mouthpiece (Battle Sports Science®) |
| ES           | Effect Size (N, 0.1–0.3(S), 0.3–0.5(M), 0.5–0.7(L)), >0.7(VL) |
| EXP          | Experiment |
| GXT          | Graded Exercise Test performed on Corival Lode® Cycle Ergometer |
| HR           | Heart Rate (bpm) |
| MAP          | Mean Arterial Pressure (mmHg) |
| NMP          | No Mouth Piece |
| O2pulse      | Oxygen pulse (mlO₂*bt⁻¹) |
| PEEP         | Positive End-Expiratory Pressure (cmH₂O) |
| PMP          | PEPP Mouthpiece |
| RER          | Respiratory Exchange Ratio calculated as VCO₂ / VO₂ (ml⁻¹*min⁻¹) |
| RPE          | Ratings of Perceived Exertion |
| RPM          | Revolutions per minute |
| TTE          | Time to Exhaustion (sec) |
| V            | O₂peakVO₂ at Voluntary Exhaustion (mlO₂*kg⁻¹*min⁻¹) |
| VT           | Ventilatory Threshold |
| VTER         | Ventilatory Threshold Endurance Ride (sec) |

Material and methods

Subjects

Thirty-two adult men and women responded to word-of-mouth and email advertisements to participate. Nineteen met our inclusionary criteria of: 1) self-reported to be physically healthy with no known contraindications for high-intensity exercise; 2) physically active as defined by regular aerobic exercise training ≥3 days per week for at least 6 months; and 3) were able to commit to the schedule required to complete all phases of testing (Table 1 Demographics). The procedures were approved by the institutional review board for research involving human subjects (IRB PRO000020755), and all volunteers signed a written informed consent prior to participating in the experimental procedures.

Description of the PMP

The PMP used in this study was a self-contained breathing device (Fig. 1) (Patent #10,252,021 and #9,555,201 B2). Not dissimilar to a traditional central-opening mouth guard often used in sports, the device has a breathing port 1½” wide x 5⅛” high to allow seamless inhalation without resistance or assistance. Upon exhalation, a thin, light-weight silicone valve deploys to obstruct the central breathing opening. Expired air is then forced through smaller openings around the outer edge of the breathing port controlled by elastic springs to open when expired pressure is greater than 4.2 cmH₂O, thereby producing mild PEEP to the wearer. The mouthpiece also has an interdental portion and buccal flange which serves to protect the teeth in a contact environment, and provides a bite surface to ensure the mouthpiece can be retained inside the mouth. Lastly, the version of the PMP device designed for use in contact sports includes a larger lip guard to further protect the user’s lips and mouth against contact.

Testing procedures

All procedures for this investigation were performed at an independently contracted laboratory (Orthopedic Biomechanics Research Laboratory, Houston Methodist Hospital, Houston TX). The laboratory altitude was 15 m above sea level (101325 Pa), and environmental conditions were controlled for all test sessions at a room temperature of 23 °C and 23% relative humidity. Two separate experiments were carried out using the same exercise protocol for each, but with different subject cohorts. EXP-1 was designed to compare maximal cycling performance using the PMP with a commercially-available mouthpiece (Battle Sports Science®) as a control. EXP-2 procedures were identical to those for EXP-1, except that cycling performance with the PMP was compared to breathing with NMP. All exercise was performed under standardized laboratory conditions, supervised by the same investigator giving verbal encouragement to the subject during exercise, and on the same electronically-braked cycle ergometer (Corival, Lode®). Continuous measures of gas exchange and HR were made using a calibrated metabolic cart with an integrated electrocardiograph (Ultima, MGC Diagnostics®). Subjects enrolled in EXP-1 and EXP-2 performed a maximal GXT at timepoint 1, and returned to the laboratory 72 h later for timepoint 2 testing to complete their VTER at an intensity equivalent to their VT (methods to follow). The following week subjects returned to complete the same order of the performance tests (testing timepoints 3 and 4), matched for time of day and day of the week, under the alternate mouthpiece condition. The mouthpiece order was assigned at random. The warm-up for all testing sessions was as follows: pedaling for 3-min at 100 W at a self-selected RPM, 1-min seated rest, pedaling for 1-min with no resistance after which the test protocol was initiated. Each subject’s self-selected RPM chosen during the initial testing session was matched during each exercise trial thereafter.

GXT

The GXT in both EXP-1 and EXP-2 was completed by each subject at timepoint 1 and 3 of their laboratory visits. Following the warm-up described above, the protocol was initiated at the subject’s self-selected RPM and an initial workload of 150 W, then increased 30 W every 2 min until exhaustion. The elapsed time from the initiation of the GXT protocol to the point at which the subject’s pedal RPM fell below their initial self-selected RPM was recorded as the GXT TTE. Variables recorded at the end of each 2-min stage and at TTE included: HR, VO₂ (ml*min⁻¹ and ml*kg⁻¹*min⁻¹), VCO₂ (ml*min⁻¹), minute ventilation RER, systolic BP and diastolic BP from manual sphygmomanometry by the same trained technician, MAP, and RPE. VO₂peak was considered valid if at least two of the following criteria were achieved; a VO₂ peak in spite of an increased workload, RER > 1.2, RPE > 17, and HR > 85% age-predicted maximal HR. At the point of exhaustion, the resistance on the ergometer was removed and subjects pedaled at their self-selected RPM for a recovery period of 5 min. All measures detailed above except RPE were recorded at 1, 3, and 5 min of recovery.

Cycle VTER

Using data from the GXT test, VO₂ at VT was calculated for each subject using the V-Slope method. Each subject’s VT-equivalent power
(W) was estimated by linear regression of stage-by-stage VO$_2$ and power output (W), then subsequently used for the VTER (sessions 2 and 4) performed 72 h after their GXT. Following their prescribed warm-up, participants were asked to maintain their self-selected RPM and VT power output until exhaustion (defined above). During the VTER and 5 min of recovery, each subject’s HR, RPE, BP, and metabolic gas exchange measures were assessed every 2 min in the same manner as during the GXT.

Statistical analysis

For EXP-1 and EXP-2, a paired sample T-test was used for comparison of all primary variables of interest, Type I Error set at $\alpha = 0.05$. Effect size was calculated using a Cohen’s D statistic for all significant pairwise comparisons and interpreted as follows: $<0.1$, negligible (N); 0.1–0.3, small (S); 0.3–0.5, moderate (M); 0.5–0.7, large (L); $>0.7$, very large (VL).

Results

Average VO$_2$peak values were as follows (mean±95%CI): EXP-1 women = 42.9±7, men = 42.2±6; EXP-2 women = 40.0±7, men = 42.8±3.2. Findings for the primary outcome variables are shown in Tables 2 and 3, and in Figs. 2 and 3. The GXT VO$_2$ and O$_2$ pulse at peak exercise were significantly greater (3.1%–6.7%, ES range 0.32[S] to 0.49 [M]) with the PMP compared with CON and NMP (Fig. 2A–D). There were no differences in measured VO$_2$ at submaximal stages by mouthpiece condition. Moreover, VO$_2$ at VT was 7% higher (ES 0.49[M]) with the PMP compared with NMP (Fig. 2F). Although not significant, VT was over 4% higher with the PMP compared to CON (Fig. 2E). These findings were observed with correspondingly greater GXT-TTE with the PMP (PMP vs CON = +26 ± 5 s, +5.8 ± 1.4%, ES 0.12[S]; PMP vs NMP = +25 ± 8 s, +5.9 ± 1.74%, ES 0.16[S]) (Fig. 3A and B). The TTE during the VTER was over 13% higher with the PMP compared with CON and NMP, but neither of these differences were statistically significant (Fig. 3C and D). During VTER, systolic BP was measured to be about 4% higher with the PMP compared with CON (Table 3).

Discussion

Medical practice has established the fact in clinical populations that the application of PEEP provides measurable benefits to pulmonary function, arterial oxygenation, and reduced postexercise dyspnea. Also, COPD patients exhibit increased exercise tolerance and lower dyspnea scores when PEEP is combined with inspiratory pressure support during cycling exercise. We are aware of only one published study prior to our own in which PEEP was applied to healthy adults performing exercise. Nespollet et al. reported that PEEP administered to healthy men significantly increased arterial and quadriceps oxygenation under normobaric and hypobaric conditions, and at 4350 m of altitude.

Our current study is the first to show that the application of mild PEEP by wearing a novel PMP during maximal exercise enhances cycling endurance performance in healthy, moderately trained men and women. Notably: 1) the exercise benefit of the PMP did not require training with the mouthpiece; 2) the gain in performance was immediate upon commencing use; and 3) the >4% improvement in VO$_2$peak, along with a nearly 6% increase in GXT-TTE, was similar to the 3–5% improvement realized by competitive runners after 21–27 days of “live high, train low” protocols. Furthermore, the minimal expiratory resistance provided...
Table 2
Results GXT at Peak Exercise: PMP vs. CON & PMP vs. NMP.

| Variable                  | Peak Exercise | Peak Exercise |
|---------------------------|---------------|---------------|
| RER (VO2/VO2)             | PMP 1.2 ± 0.06 | PMP 1.3 ± 0.06 |
|                           | CON 1.2 ± 0.04 | NMP 1.2 ± 0.06 |
|                           | Diff. 0.02 ± 0.06 | Diff. 0.02 ± 0.03 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | Size |       | Size |       |
| Watts                     | PMP 268.7 ± 35.9 | CON 260.0 ± 35.3 |
|                           | NMP 258.0 ± 25.1 |
|                           | Diff. 6.6 ± 8.6 | Diff. 3.0 ± 5.3 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | Size |       | Size |       |
| Systolic BP (mmHg)        | PMP 186.0 ± 9.6 | CON 193.3 ± 10.9 |
|                           | NMP 171.8 ± 15.4 |
|                           | Diff. −7.3 ± 5.9 | Diff. −5.4 ± 7.0 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | * (4.47(M) |       | NS |       |
| Diastolic BP (mmHg)       | PMP 73.8 ± 4.5 | CON 74.4 ± 5.0 |
|                           | NMP 67.6 ± 5.7 |
|                           | Diff. −0.7 ± 3.8 | Diff. 1.0 ± 2.9 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| Mean Arterial BP (mmHg)   | PMP 111.2 ± 5.5 | CON 114.1 ± 5.6 |
|                           | NMP 104.1 ± 8.5 |
|                           | Diff. −2.9 ± 3.5 | Diff. −1.1 ± 3.5 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| Heart Rate (bpm)          | PMP 185.1 ± 4.9 | CON 184.4 ± 5.5 |
|                           | NMP 178.6 ± 5.4 |
|                           | Diff. 0.6 ± 1.7 | Diff. 1.6 ± 1.6 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| Minute Ventilation (L/min)| PMP 128.7 ± 22.7 | CON 119.6 ± 19.6 |
|                           | NMP 123.1 ± 12.9 |
|                           | Diff. 9.1 ± 9.7 | Diff. 5.9 ± 10.1 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |

Table 3
Results ventilatory threshold endurance ride (VTER).

| Variable                  | Average | Average |
|---------------------------|---------|---------|
| RER (VO2/VO2)             | PMP 1.1 ± 0.04 | CON 1.1 ± 0.07 |
|                           | Diff. 0.0 ± 0.05 | Diff. 0.0 ± 0.03 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | Size |       | Size |       |
| Watts                     | PMP 197.8 ± 22.9 | CON 197.8 ± 22.9 |
|                           | NMP 196.6 ± 6.3 |
|                           | Diff. − | Diff. |
|                           | Sig. | Effect | Sig. | Effect |
|                           | Size |       | Size |       |
| Systolic BP (mmHg)        | PMP 178.0 ± 10.0 | CON 171.2 ± 10.0 |
|                           | NMP 166.6 ± 13.5 |
|                           | Diff. 6.8 ± 5.7 | Diff. −4.5 ± 4.7 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | * (0.04(M) |       | NS |       |
| Diastolic BP (mmHg)       | PMP 73.5 ± 5.7 | CON 70.5 ± 3.6 |
|                           | NMP 65.1 ± 4.4 |
|                           | Diff. 2.2 ± 5.3 | Diff. 1.4 ± 2.0 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| Mean Arterial BP (mmHg)   | PMP 108.3 ± 6.3 | CON 104.0 ± 6.1 |
|                           | NMP 98.4 ± 6.9 |
|                           | Diff. 3.5 ± 4.5 | Diff. −0.6 ± 2.3 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| VO2(L/min⁻¹)              | PMP 2.5 ± 0.4 | CON 2.5 ± 0.4 |
|                           | NMP 2.5 ± 0.4 |
|                           | Diff. 0.0 ± 0.1 | Diff. 0.1 ± 0.1 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| Heart Rate (bpm)          | PMP 170.9 ± 5.1 | CON 170.2 ± 4.5 |
|                           | NMP 162.7 ± 6.3 |
|                           | Diff. −0.4 ± 0.6 | Diff. 0.6 ± 2.8 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |
| Minute Ventilation (L/min)| PMP 78.5 ± 17.4 | CON 78.2 ± 13.9 |
|                           | NMP 81.9 ± 9.6 |
|                           | Diff. 3.8 ± 8.5 | Diff. 0.3 ± 3.1 |
|                           | Sig. | Effect | Sig. | Effect |
|                           | NS |       | NS |       |

Values mean ± 95%CI, * p < 0.05. ES = <0.1 (N), 0.1–0.3(S), 0.3–0.5(M), 0.5–0.7(L), >0.7(VL).

by the PMP did not alter breathing patterns during strenuous exercise. This was demonstrated in our study by the fact that there were no significant differences in average and peak ventilatory rates between PMP, NMP, and CON conditions during the VTER and GXT sessions (Tables 2 and 3).

The VT was improved 4.1%–7.4% with the use of the PMP (Fig. 2E and F). In this regard, an increase in VT relative to VO2max has been shown to be related to an improved endurance performance, and raising the VT is often a goal of endurance training. Others have shown that a significant improvement in VT generally requires at least 8–12 weeks of repeated high-intensity training bouts at or above the baseline VT. By contrast in our study, the PMP increased VT during a single, intense exercise session without prior training. Though training studies with the PMP have yet to be completed, we suggest that the higher VT with PMP would enable competitive athletes to train at relatively higher intensities with less fatiguing lactate accumulation and related pH changes.

The PMP also resulted in a 13%–14% increase in TTE during the VTER (Fig. 3C and D). Although this would be considered a meaningful benefit by competitive athletes, in our study the improvement did not reach statistical significance. Indeed, we recommend caution in interpreting both the GXT-TTE and VTER TTE findings. Others have shown TTE to be subject to a number of confounding factors which are difficult to control, and which likely contributed to the wide variation of the individual responses noted in our study (Fig. 3). Furthermore, TTE has been shown to be an unreliable predictor of actual cycling time trial performance. In spite of this time-trial reliability question, other researchers have shown TTE to be sensitive to changes in endurance performance. On this basis, we suggest that at least the significant increase in the GXT-TTE represents a real change in subject endurance performance with the PMP. However, since we did not perform a cycling time trial test, we make no inference to an increase in time trial performance with the PMP.

The comparatively higher O2pulse with the PMP during maximal exertion on the GXT is consistent with the elevated VO2peak measured in this study. Since O2pulse is a function of heart stroke volume, we speculate that the PMP induced an increase in this cardiac variable at max exercise compared with CON or NMP conditions. Though we have no direct measure of stroke volume in our study, Bhambhani has shown that this cardiovascular performance variable can be reasonably predicted in healthy men and women from O2pulse. Applying Bhambhani’s regressions to our data suggest an estimated increase in stroke volume of approximately 3–4% in our subjects averaged across both experiments. Such an increase with the PMP would at least partially explain the improvement in VO2peak.

Although we did not design our study to investigate the mechanism by which the PMP improved performance (e.g., VO2peak), clinical literature suggests the mild PEEP could improve alveoli recruitment and reduce pulmonary shunting. We also point out that the PMP is different in design and function from elevation training masks, which
have been applied to exercise training. (e.g., Welnetz’ patented design26). By comparison, the elevation training masks generally simulate altitude by employing filters to decrease oxygen density of inhaled air, and provide inspiratory and expiratory breathing resistance. Porcari et al. 27 reported no significant advantage of mask training for improvements in \( VO_2max \) in moderately trained adults, and concluded that the mask did not simulate altitude. The majority of other published research supports these findings.27–30 There are no published studies showing a performance advantage of using elevation training masks during competition or while actually performing a single session of heavy exercise (e.g., during an exercise test). This is in contrast to the performance improvement realized during a single session of exercise with the PMP.

Conclusions

Our results demonstrated that mild PEEP produced by a lightweight, wearable PMP was an effective and safe means to acutely improve performance in high-intensity, maximal effort cycling exercise. These benefits were without negative consequences on any of the performance or cardio-pulmonary variables measured. Whether or not the PMP augments long-term physical training of various training durations, intensities, and modalities remains to be determined, though such a training benefit is a reasonable hypothesis. It is also possible that this technology could be of advantage when oxygen supply is limiting
exercise, such as at altitude, in certain cardiopulmonary disease conditions, or when personal protective masks must be worn by first responders. Future research is needed to determine the mechanisms responsible for PMP effectiveness, and to verify our findings in other trained and untrained men and women engaged in other modes of exercise.

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Submission statement

The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The manuscript has not been published and is not under consideration for publication elsewhere.

Ethical approval

The procedures were approved by the institutional review board for research involving human subjects (IRB PR000020755), and all volunteers signed a written informed consent prior to participating in the experimental procedures.

Authors’ contributions

SFC; study research design, data collection & analyses, manuscript development.
JRL; data analysis, assistance on manuscript development.
SB; design of PMP, study research design, contribution to manuscript.
WB; study design and subject recruitment.
MM; consulted on research design.
PMM; provided laboratory resources for carrying out data collection.
BSL; study research design, subject recruitment, data collection and analyses, manuscript development.

Conflict of interest

The authors declare no competing interests. We wish to draw the attention of the Editor to the following facts which may be considered as potential conflicts of interest and to significant financial contributions to this work.

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