Influence of an Exercise-Specific Face Mask on Physiological, Respiratory, and Perceptual Responses to Graded Exercise in Aerobically Fit Individuals

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Abstract

Introduction: Research indicates that there are no health risks associated with face mask use during exercise in healthy individuals. However, the impact of a face mask on physiological, perceptual, and performance responses to exercise of all intensities remains equivocal. Evidence suggests mask use during exercise elevates perception of effort with marginal impact on physiological responses, where the influence on performance remains contested. Furthermore, there is limited research on the perceptual, respiratory, and physiological responses to different exercise intensities with masks that have been marketed for "exercise use" (exercise specific face mask - ESFM). There is also evidence to suggest a respiratory protective benefit to wearing a face covering during exercise in those with exercise-induced bronchoconstriction (EIB). Thus, the overall suitability of ESFM use in athletes and other aerobically fit individuals remains unclear.

Objective: To determine the physiological, respiratory, perceptual, and performance effects of an ESFM during submaximal and maximal-intensity exercise in aerobically fit individuals. It was hypothesized that ESFM use would elevate perceptual burden in the absence of physiological changes, impairing exercise performance. Furthermore, it was hypothesized that ESFM use would help to preserve respiratory function in individuals with EIB.

Methods: Twenty-four individuals (11 females) underwent a discontinuous graded exercise test on a treadmill on two separate occasions. These two trials (ESFM and unmasked) were completed in a randomized order at least 72 hours apart. Physiological measures, perceptual measures, and respiratory function were assessed throughout the test, which was performed in ambient indoor conditions (19-20°C, 2-8 mg H_2O/L). Heart rate, respiratory rate, blood oxygen saturation (SpO_2), dyspnea, rating of perceived exertion (RPE), and respiratory function were measured at the end of each stage and at termination. Performance was assessed by time to exhaustion and based on the last stage of the protocol completed. Linear mixed modeling was used to identify significant differences across 4 submaximal intensities for physiological and perceptual measures. Submaximal spirometry measures were analyzed via repeated measures analysis of variance. Pairwise comparisons were used to analyze responses associated with maximal-intensity exercise. An alpha value of 0.05 was used to indicate significant differences.

Results: Performance was significantly impaired when an ESFM was worn (median= -150.5 s). SpO_2 was significantly decreased in the masked condition for both submaximal and maximal intensity (-3.7%) exercise, with no significant differences observed in respiratory rate or heart rate. Perceptions of both air hunger and work of breathing were elevated across both submaximal and maximal exercise intensities. RPE and breathing discomfort were significantly elevated submaximally but not at termination, with no differences in chest tightness, throat tightness, or leg discomfort at any exercise intensity. Spirometry measures were not significantly different at exercise termination, but in the ESFM condition, several measures of respiratory function were significantly elevated submaximally.

Conclusion: Use of an ESFM in fit individuals imposes a perceptual burden via increased perceptual discomfort, which was observed in several measures during both submaximal and maximal exercise intensities. In combination with heightened arterial desaturation in the ESFM condition, exercise performance was also impaired. The combination of these physiological and perceptual changes likely contributed to the observed performance

impairment. However, the sizable improvements in respiratory function particularly in spirometry measures sensitive to changes in peripheral airway caliber would indicate that ESFMs are a ‘double-edged sword’, promoting bronchodilation at the cost of elevated perceptual sensations and arterial desaturation in both individuals with and without EIB.

Preface

This thesis is original work by Aidan K. Comeau. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board ("Influence of a face mask on perceptual, physiologic, and respiratory function to outdoor running at different intensities.", Pro00107700, April 6, 2021).

This research project was originally conceived by M.D. Kennedy and C.D. Steinbeck. A.K. Comeau was responsible for the data collection and analysis as well as the composition of this thesis. N. Paradoski and S. Bozic assisted with data collection. E. Parent provided additional guidance for statistical analysis. K.E. Jones and M.D. Kennedy contributed to manuscript revisions.

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List of Abbreviations

Abbreviation	Description
ACSM	American College of Sport Medicine
AH	Air hunger
BD	Breathing discomfort
CT	Chest tightness
EIB	Exercise-induced bronchoconstriction
EIB-	Identified as not having exercise-induced bronchoconstriction
EIB+	Identified as having exercise-induced bronchoconstriction
ESFM	Exercise-specific face mask
f	Respiratory frequency (breaths/min)
FEF_{25-75}	Forced expiratory flowrate from 25%-75% expired volume (L/s)
FEF_{50}	Forced expiratory flowrate at 50% expired volume (L/s)
FeNO	Fractional exhaled nitric oxide (PPB)
FEV_1	Forced expiratory volume in one second (L)
FFP2	Filtering facepiece: class two
FVC	Forced vital capacity (L)
GXT	Graded exercise test
HR	Heart rate (beats/min)
LD	Leg discomfort
Min/km	Minutes per kilometer
OHDC	Oxyhemoglobin disassociation curve
$PaCO_2$	Arterial partial pressure of carbon dioxide (mmHg)
P_ACO_2	Alveolar partial pressure of carbon dioxide (mmHg)
PaO_2	Arterial partial pressure of oxygen (mmHg)
PEF	Peak expiratory flow (L/s)
$P_{ET}CO_2$	Partial pressure of end-tidal carbon dioxide
PFM	Protective face mask

Abbreviation	**Description**
$_{P}$WOB	Perceived work of breathing
RH	Relative humidity (%)
RPE	Rating of perceived exertion
SMD	Standard mean difference
SpO_2	Arterial oxygen saturation (%)
TT	Throat tightness
$\dot{V}CO_2$	Carbon dioxide production (L/min)
VD	Ventilatory dead space
$\dot{V}_E$	Minute ventilation (L/min)
$\dot{V}O_2$	Oxygen uptake (L/min)
$\dot{V}O_2$ max	Maximal aerobic power (L/min)
V_T	Tidal volume (L)
WOB	Work of breathing
$_{END}$GXT	Time of termination in a graded exercise test

Chapter 1: Introduction

Amid the COVID-19 pandemic, caused by viral infection with Severe Acute Respiratory Syndrome Coronavirus 2, the use of a protective face mask (PFM) was widely encouraged to limit person-to-person viral transmission. Although the recommendation of mask-wearing in indoor public spaces was nearly ubiquitous during the pandemic, recommendations surrounding their use while performing physical activity varied substantially (1). In January 2022, the World Health Organization (2) recommended that individuals should not wear PFMs while exercising as it may restrict a person's ability to breathe comfortably and rather, recommended physical distancing from others to mitigate viral spread. The American Centres for Disease Control (3) made a more nuanced recommendation, maintaining that the use of PFMs was appropriate for low-intensity physical activity. Canadian guidelines as of 2021 included wearing PFMs for low-intensity indoor physical activity but did not recommend their use for high-intensity activity (4). Given the uncertainty as to the interaction between mask use and physical activity, research investigating the physiological, perceptual, and performance impacts of PFM use has been conducted.

Contemporary research has provided insight into mask-wearing across a spectrum of exercise modalities, mask types, and exercise intensities. A 2022 meta-analysis on the subject identified 45 studies published prior to April of 2022 that investigated the physiological, perceptual, and/or performance impacts of mask-wearing during exercise (5). Although existing research has provided significant insight into the potential impact of mask-wearing on a variety of measures, there are still factors in this relationship that have yet to be fully elucidated. A 2022 narrative review by Prado et al. (6) suggested that mask use during exercise should be contextualized through several factors including a) mask type, b) individual characteristics such as age, sex, and fitness level, c) activity characteristics including modality, intensity, and duration & d) environmental characteristics such as temperature and humidity. When appraised through this framework, modifying any one of these factors may influence physiological and perceptual responses to physical activity with a PFM. Moreover, Prado et al. (6) specifically called for further research on “different types of respiratory face masks in athletes”, identifying aerobically fit individuals as a unique cohort in need of specific scientific inquiry.

Although our understanding of the impact of PFM use during exercise is much improved given the advent of more research examining exercise and face coverings, there are still gaps in the literature that need to be addressed. Although research has been conducted on a variety of mask types including those designed to filter 95% of airborne particles (N95 in North America and FFP2 in Europe), surgical, cloth, and even self-contained breathing apparatuses and their various impacts during exercise, there is a paucity of research investigating the use of exercise-specific face masks (ESFMs) during high-intensity exercise, where an elevated ventilatory demand is driven by metabolic oxygen consumption and carbon dioxide production (7). Provided that different types of masks may have a differential impact when it comes to individual physiological and perceptual responses (8), a mask designed for high-ventilation activities would likely be better suited for use during exercise when compared to more traditional PFMs. Therefore, ESFMs may impose a smaller physiological and perceptual burden when used during exercise. Additionally, although several studies have examined PFM use during exercise in both clinical and healthy populations (5, 8), responses in aerobically fit individuals using ESFMs have yet to be thoroughly investigated. Given that trained aerobic athletes can achieve minute ventilations ($\dot{V}_E$) over 200 liters per minute (9), their elevated respiratory demands likely effect perceptual and physiological responses to a greater degree than in untrained individuals.

Finally, no research has examined the potential of ESFMs in preventing the onset and/or severity of exercise-induced bronchoconstriction (EIB) during exercise. Previous research has indicated that the use of a heat & moisture exchange mask can help attenuate post-exercise reductions in lung function in individuals with EIB (10-12) but the strength of evidence in this area remains weak (13). Current guidelines from the American Thoracic Society also list the use of a scarf or buff over the face as a recommended non-pharmacological means of attenuating EIB (13), however, the empirical evidence to support this recommendation is limited in scope (14). Furthermore, there is evidence to suggest some individuals with EIB experience an acute reduction in respiratory function during prolonged exercise (15), often referred to as breakthrough EIB. Ultimately, it is still unclear whether simple cloth face coverings are an effective means of preserving respiratory function during exercise in those with and without EIB.

Given the unique physiological demands of fit individuals and the paucity of research examining ESFMs, this research project aimed to determine if ESFMs had a significant impact on the physiological, respiratory, and perceptual responses of aerobically fit individuals completing submaximal and maximal-intensity exercise in typical indoor ambient conditions. Additionally, we sought to determine if the use of an ESFM impaired exercise performance. Finally, this study also aimed to determine if an ESFM could alter within-exercise changes in respiratory function associated with EIB. The findings of this study contribute to the scientific knowledge on face covering use and human exercise physiology, helping to inform mask users as to the potential physiological, respiratory, perceptual, and performance effects of ESFM use.

Chapter 2: Literature Review

2.1 Theoretical Influence of a Face Mask on Pulmonary Physiology

A 2021 narrative review by Hopkins and colleagues (16) attempted to make sense of the mechanisms by which a PFM could potentially impact exercise and original research by Doherty et al. (17) discussed potential mechanisms of influence associated with PFM use during exercise. Although properties vary between different mask types, physiological and perceptual impacts during exercise likely stem from several primary factors that are elucidated in subsequent paragraphs: a) airflow resistance, b) external dead space, c) inspired temperature & humidity, and d) modified perceptual sensations.

2.1.1 Airflow resistance.

Although airflow resistance is a necessary element of PFM function (16), its impact may be detrimental when introduced during exercise. The degree of airflow resistance imposed by a PFM is a product of its construction, materials, and intended application in addition to the respiratory flow rate of the user. When measured at a standardized continuous flow rate of 85 L/min, N95 masks approved by the United States National Institute for Occupational Safety and Health may impose up to 3.5 cmH_2O of airflow resistance (18), although many commercial N95s fall far below this threshold, eliciting levels of resistance closer to 1.5 cmH_2O (19). Less protective masks like surgical and cloth masks impose even less resistance, with resistances of under 1.0 cmH_2O (16). Imposed airflow resistance is more variable in cloth face coverings as the materials used in mask construction play a large role (20), where work by Rengasamy and colleagues (21) demonstrated that different fabric types tested at a similar flow rate had resistances between 0.04 cmH_2O and 0.59 cmH_2O. Therefore, although the material utilized alters resistance from product to product, the resistance imposed by all types of PFMs is significantly less than those with external resistors intended for respiratory muscle training, where resistance can be 5-10 times that imposed by a typical PFM (16). Additionally, given laboratory assessments use a continuous flow rate of 85L/min to characterize PFM resistance (22), this fails to provide a clear understanding of the resistance imposed at flow rates experienced during high-intensity exercise, which can exceed 10 times that of rest in trained individuals (23). Furthermore, it is known that as flow rates increase, so does the resistance imposed by a PFM, and this increase is not necessarily linear (16).

Imposed external resistance has the potential to increase the metabolic cost associated with respiration or work of breathing (WOB). Submaximally, this may manifest as an increase in the metabolic demand of respiration, observable via increases in whole-body aerobic metabolism ($\dot{V}O_2$) and heart rate (HR) (24). With prolonged exercise, imposed airflow resistance may also accelerate respiratory muscle fatigue. Although potentially non-consequential at rest or light to moderate exercise intensities as defined by the American College of Sport Medicine (ACSM) (25), high-intensity physical activity significantly increases WOB due to increased ventilatory demand, with respiratory muscles demanding 13-15% of total $\dot{V}O_2$ at one's maximal rate of oxygen consumption ($\dot{V}O_2$ max) (26). This likely has real-world implications for aerobically fit individuals through activation of the respiratory muscle metaboreflex (6). This occurs when respiratory muscle fatigue brought about via sustained high WOB leads to the redistribution of cardiac output via sympathetically mediated limb vasoconstriction (27). This can impair peripheral oxygen transport leading to accelerated muscle fatigue and increased perception of effort (28). This diversion of blood flow may also impair performance, particularly in sustained efforts over 85% $\dot{V}O_2$ max (29). Although this phenomenon can occur during exercise without a PFM, the added resistance associated with PFM use may expedite its onset or increase its likelihood of occurring. Research by Dominelli and colleagues (30) identified a competitive relationship between respiratory and locomotor muscle blood flow, with added external breathing resistance significantly increasing blood flow to the respiratory muscles while simultaneously decreasing flow to the limbs during intense exercise at 90% maximal aerobic power. Although the imposed resistance of 1.25-5.0 $cmH_2O/L/s$ was greater than that imposed by a PFM (16), this relationship indicates that increases in breathing resistance may lead to a redistribution of cardiac output, potentially impairing performance via a reduction in blood flow and associated oxygen delivery to active skeletal muscle.

2.1.2 External dead space.

External dead space is another potential source of physiological and perceptual differences during exercise with a PFM. At rest, approximately 30% of inspired air constitutes anatomical dead space, which is air that remains in the conducting airways and does not undergo gas exchange (31). Although anatomical dead space is an inherent physiological phenomenon, additional external dead space can also be imposed by respiratory protective devices like self-contained breathing apparatuses (32) and PFMs (33), effectively adding to the volume of anatomical dead space. As both anatomical and external (or imposed) dead spaces are similar in that they contain air that never reaches the alveoli, they are both referred to as simply ventilatory dead space (VD) hereafter. As with airflow resistance, the amount of additional VD imposed varies between different types of PFMs. Furthermore, both mask size and face shape/size influence the amount of imposed VD, with a study of different N95 masks finding they added between 98.4ml to 165.7ml of VD (33). These numbers are reflective of work by Elbl and colleagues (34), who examined several different models of PFM with VD increases of 89ml to 204ml. Provided that traditional cardiopulmonary exercise testing systems impose ~100ml of external VD (35), exercise with a PFM likely imposes a comparable degree of VD to that of an individual who is undergoing a laboratory-based aerobic exercise assessment.

Many studies have examined the impact of additional VD imposed during exercise. Given that direct analysis of arterial blood gas tension is invasive, surrogate measures are often used during exercise including end-tidal and alveolar gas tensions, which are derived from expired gas analysis (36, 37). Although modest increases in VD at rest (<500ml) are adequately compensated for via hyperpnea to maintain a typical resting alveolar CO_2 partial-pressure (P_ACO_2) of 36 to 42 mmHg (7, 36), the ventilatory response to VD loading may be sub-optimal during exercise. When engaged in light exercise, the respiratory response to VD loading does not appear to be adequate to maintain P_ACO_2, a trend that has been observed across imposed VD volumes of +250ml to +500ml (38). This is supported by a meta-analysis by Zheng and Colleagues (5), who found that end-tidal carbon dioxide ($P_{ET}CO_2$) was increased both during steady-state exercise (+2.09 mmHg) and at graded exercise test termination (+4.15 mmHg) when a PFM was worn. Given that CO_2 tension in arterial blood (P_aCO_2) is the driving force behind changes in ventilation, with an increase as small as 1mmHg being able to stimulate increased ventilatory drive (39), any changes in respiration stemming from arterial blood gas tension when a PFM is worn are likely attributable to changes in P_aCO_2 rather than changes in arterial oxygen tension (P_aO_2).

Although hypoxia induced by mask-wearing was a concern raised early in the COVID-19 pandemic (40), a meta-analysis by Zheng et al. (5) found arterial oxygen saturation (SpO_2) was reduced in healthy individuals at $\dot{V}O_2$ max with a PFM, although the mean reduction of 0.6% when compared to unmasked exercise is likely of minimal practical significance, given the mean SpO_2 of most studies included was still greater than 95%. Provided SpO_2 values >90% typically fall on the 'flat' portion of the oxyhemoglobin disassociation curve (OHDC) (41), relatively large reductions in PaO_2 would be required to see substantial reductions in SpO_2. Despite this, the combined effect of exercise and elevated P_aCO_2 brought about through dead space rebreathing may result in an accentuated rightward shift of the OHDC, making reductions in SpO_2 more likely. Although few studies in the field have assessed blood gas tension directly in the context of exercise and PFM use, work by Fikenzer and colleagues (42) found no significant differences in P_aO_2 or P_aCO_2 as determined by a capillary blood sample assessed at $\dot{V}O_2$ max with a PFM in healthy individuals when compared to unmasked exercise. This runs counter to the findings of Marek et al. (43) however, who found P_aCO_2 assessed via capillary blood gas analysis to be significantly elevated during heavy-intensity exercise ($\dot{V}_E$= 60L/min) across several PFM types including surgical (+3.04 mmHg), cloth (+2.71 mmHg), and FFP2 (+4.71 mmHg) when compared to no mask. Thus, given conflicting findings in relation to blood gas tensions and arterial oxygen saturation, it remains unclear if PFM use during exercise substantially alters pulmonary gas exchange.

Imposed VD during exercise may also alter respiratory dynamics, with larger increases in tidal volume (V_T) being observed as a compensatory response to VD loading during graded exercise (44), a strategy that allows for more 'fresh' ambient air to be inspired, effectively decreasing the percentage of V_T that is VD (16). A case study by Prado et al. (24) observed this pattern, with the ratio between breathing frequency (*f*) and V_T being significantly lower across all exercise intensities when a PFM was used, indicating that larger less-frequent breaths were employed to cope with conditions imposed by facemask use. This finding is not universal, however, as research by Rojo-Tirado and colleagues (45) found that although f was decreased, mean V_T remained largely unchanged, with a corresponding reduction in $\dot{V}_E$ when an FFP2 mask was worn, both at the first ventilatory threshold (-19.3%) and peak exercise (-22.3%). Although with added VD alone, a compensatory increase in V_T would be expected with minimal change in f (38), the combined resistance & VD imposed by a PFM may alter this traditional response, with the added resistance making it more difficult to adequately increase V_T. This suggests that the resistance imposed by the PFM in combination with the additional VD may result in hypoventilation, potentially altering arterial blood gas tensions during exercise.

2.1.3 Inspired temperature & humidity.

PFMs can also increase both the temperature and humidity of inspired air. Work by Courtney & Bax (46) utilized a novel method to estimate changes in the water content of inspired air when a PFM was worn, illustrating that use of a PFM at room temperature can increase the apparent relative humidity (RH) of inspired air by between 38 – 90%, with heavy cloth masks being most effective at increasing inspired humidity. This effect was even more pronounced under cool environmental conditions (8°C), with surgical, N95, and fabric PFMs increasing RH by over 150% (46). The PFMs also functioned to heat the inspired air, as although not measured directly, the high heat capacities of modern PFMs allow for the storage of heat from expired air that is utilized to warm air upon inspiration (46). When the surface temperature of the PFM was measured immediately following expiration, the temperatures were consistently 30°C, even though environmental conditions were a much cooler 8°C (46). Provided that the ability for air to hold water increases exponentially with temperature increases, the combination of increased heat and RH substantially augments the absolute water content of inspired air, with PFMs adding between 12–24 mg H_2O/L air (46).

Although existing research has examined the efficacy of specialized heat & moisture exchange masks to reduce the severity and onset of EIB in cold weather conditions (47), little has been done to examine the potential protective benefit of more simple face coverings under typical indoor conditions. The ACSM recommends that fitness facilities maintain an ambient temperature of 20-22°C with a RH of ~50% (48). Although seemingly benign, these conditions are associated with a low absolute humidity of <10mg H_2O/L of air, which may provoke the airway during exercise (49). Provided air needs to be conditioned to approximately 44mg H_2O/L of air by the time it reaches the alveoli (50), even indoor ambient conditions can pose a challenge for adequate humidification when paired with high ventilatory demands associated with exercise (51). The continued humidification and warming of inspired air before it reaches the peripheral airways is important for the maintenance of optimal airway function (52). Acutely, sub-optimal conditioning of inspired air can hinder mucociliary clearance and induce adverse respiratory symptoms (53). Chronically, inadequate conditioning of inspired air can also lead to ciliary and epithelial damage (54), which has been associated with the development of airway smooth muscle hyperresponsiveness (23). Given that the ability to adequately condition inspired air is challenged with exercise-induced hyperpnea and with dry/cold environmental conditions, exercise in fit individuals under dry conditions poses a significant challenge to the respiratory system. At rest ($\dot{V}_E$ <15 L/min), inspired air at typical ambient indoor conditions is primarily conditioned by the proximal airways (51). However, when ventilating at over 100 L/min, more distal airways are brought into the conditioning process, with inspired air being significantly colder than basal conditions at all points proximal to the sub-segmental bronchi when compared to rest (51). This difference is even more pronounced in cold air conditions (-18.6 °C), with the inspired air temperature remaining significantly below basal conditions at the subsegmental bronchi (51). Given the relationship between air temperature and absolute humidity is curvilinear, reduced air temperature also indicates a lowered absolute water content for the same RH, resulting in an increased burden of conditioning in the peripheral airways (53).

Alterations in the temperature and/or humidity of inspired air can also increase the likelihood of someone experiencing EIB. Although the collective understanding of the mechanistic underpinning of EIB has evolved significantly over the last 50 years (55), increasing evidence has shown the inspiration of comparatively dry air as being the primary driving force behind EIB. When air is inhaled, the conducting airways act to rapidly warm and humidify inspired air to basal conditions (37°C, saturated with water vapor) before reaching the alveoli, a process which is reversed upon expiration (50). The osmotic hypothesis of EIB postulates that conditioning large volumes of relatively dry inspired air leads to dehydration of the airway surface liquid (55). Subsequently, moisture contained within the epithelium of the airway moves to replenish the airway surface liquid due to the formed osmotic gradient (55). As cells surrounding the airway lumen become hyperosmolar, with increased concentrations of calcium and inositol triphosphate, the release of inflammatory mediators is triggered, ultimately leading to airway smooth muscle contraction (55). Mast cells are a form of granulocyte that are often considered the primary source of mediators for bronchoconstriction (56), which when triggered, degranulate releasing prostaglandins, leukotrienes, histamine, and tryptase (57). These mediators are associated with numerous airway responses including bronchial smooth muscle contraction, increased mucus production, increased vascular engorgement, and edema, all of which act to reduce airway caliber (58). Airway cooling has also been proposed as a potential mechanism for EIB via the thermal hypothesis, which poses that rapid airway rewarming after exercise cessation leads to reactive hyperemia of the airway microvasculature and edema, effectively narrowing the airways (55). Although this may be a contributing factor, particularly with cold weather exercise, it has been demonstrated that EIB can still occur when inspiring hot dry air (35°C, 25% RH) (59). This shows that thermal changes are not necessary to induce EIB and that any environmental conditions with relatively low absolute humidity (<10 mg H_2O/L of air) can challenge the airway's ability to condition inspired air during exercise (49). Thus, given that airway dehydration appears to be the driving force behind EIB under temperate indoor conditions, any means of increasing a) the absolute water content of inspired air or b) the amount of water recovered upon expiration is likely to reduce the degree of this response. Although it is relatively difficult and often impossible to modify environmental conditions when training and competing, personal interventions such as use of a face covering can effectively increase inspired water content, potentially attenuating or preventing EIB.

Although increasing the temperature and humidity of inspired air is beneficial from a lung health perspective, this may have an inadvertent impact on thermoregulation during exercise. Under typical indoor ambient conditions at rest, approximately 10% of metabolic heat loss is attributable to respiration (60). Given the ability of PFMs to store both heat and humidity, the use of a PFM during exercise may restrict an individual's ability to expel excess heat via convective and evaporative means through respiration, which could elicit additional thermoregulatory strain during exercise (60). A study by Yoshihara and colleagues (61) attempted to elucidate this. Interestingly, they found no significant differences in rectal temperature during 60 minutes of light to moderate intensity exercise in environmental temperatures exceeding 30°C across several types of face coverings, including N95, surgical, gaiter, and ESFM (61). This is further supported in work by Kim et al. (62), who found that N95 masks did not significantly elevate rectal or global skin temperature during one hour of treadmill walking in a hot environment (35°C, 50% RH). Research by Roberge and colleagues also supports this notion, with core temperature not being significantly elevated when an N95 was worn during up to two hours of low to moderate-intensity work in ambient indoor conditions (63). Given no significant differences in core temperature were found in hot environmental conditions, it is unlikely that thermoregulation would be impaired under temperate indoor conditions (20°C, 50% RH) or with shorter duration activity when a PFM is worn. In tandem, these findings suggest that if any additional thermal strain is induced through PFM use, it is compensable via other cooling mechanisms, given core temperatures were not significantly elevated.

2.1.4 Modified perceptual sensations.

Perceptions and sensations play a crucial role in understanding responses to PFM use during exercise. Among the many sensations that may arise from PFM use, changes in the rating of perceived exertion (RPE) and shortness of breath (dyspnea) are commonly used quantitative measures of perception during exercise in PFM research (5). While measures such as fatigue and thermal sensation have also been employed to examine the perceptual impact of PFMs during exercise, these metrics have been less frequently evaluated compared to RPE and dyspnea (5). The perceptual experience of wearing a PFM is likely a key factor in when a person decides to use one, and these perceptual measures provide meaningful insights when studying PFM use during exercise.

RPE is a commonly used metric to assess an individual's overall perception of physical exertion during exercise. While the exact mechanisms underlying this process are not yet fully understood, it is evident that both biological mechanisms and top-down psychological constructs contribute to RPE (64). The primary assertion from this psychobiological model is that an individual's RPE serves as a reliable indicator of their limits and is linked to the concept of a central limiting factor in exercise performance (65, 66). Biological contributions to RPE include afferent feedback from cardiovascular and peripheral sources that are integrated centrally, contributing to one's perception of effort during exercise (64). The association of RPE with biological mechanisms is supported by correlations with metabolic and cardiac parameters of exercise intensity, showing a strong positive association with HR and blood lactate, independent of sex, age, and fitness level (67). The contribution of psychological constructs to RPE is supported by studies that demonstrate factors like music type (68) and mental fatigue (69) can influence RPE without corresponding physiological changes. Therefore, the use of a PFM during exercise may potentially elevate RPE, either in response to physiological changes or even in their absence, potentially impacting peak exercise performance.

Elevated sensations of dyspnea, defined as the "subjective experience of breathing discomfort" (70), have also been observed when a PFM is worn during exercise (5). Although frequently assessed, inconsistencies in the way dyspnea has been defined make identifying its potential physiological source challenging (71). Dyspnea in the context of respiratory disease often has a physiological source that "alters the function of the respiratory pump, increases the work of breathing, and reduces the ability to achieve appropriate flow, [tidal] volume, and gas exchange" (72). Although the specifics of this process differ depending on the morbidity in question, the source of dyspnea in disease is often multifactorial, with potentially several underlying pathophysiological mechanisms (73). In contrast, so-called 'exertional dyspnea' has also been observed during exercise in healthy individuals, with perceived breathlessness being subjectively attributed to rapid and heavy breathing (74). Exertional dyspnea can also be exacerbated in aerobically fit individuals with conditions such as EIB or exercise-induced laryngeal obstruction (EILO) (75). Although once thought to be a singular entity with varying degrees of intensity (76), it is now understood that the different associated sensations of dyspnea can be distinguished, giving further insight into the potential physiological source (74).

The pulmonary changes associated with PFM use including VD loading, increased airflow resistance, and altered inspired gas conditions have all been shown to elevate sensations of dyspnea (73), although the mechanism by which they each act is likely unique. Additional dead space increases inspired PCO_2 leading to increased P_aCO_2 (77), which triggers sensations of 'air hunger' (AH) via afferent signaling from central and peripheral chemoreceptors that are sensitive to changes in blood gas tension, particularly changes in P_aCO_2 (78). This response is intended to increase ventilatory drive, stimulating hyperpnea to return blood gasses to a state of homeostasis (79). Increased airflow resistance heightens the load on respiratory muscles and may lead to premature respiratory muscle fatigue, both of which can acutely elevate perceived work and effort of breathing ($_P$WOB) via afferent mechanoreceptor signaling from respiratory muscles that when interpreted indicates respiratory effort is greater than typical for a given V_T (78). Increasing the temperature and humidity of inspired air reduces the burden of air conditioning, potentially attenuating bronchoconstriction (52), which often manifests as an increased sensation of chest tightness (CT) (78). Under severe bronchoconstriction, ventilation may be adversely impacted to the point where gas exchange is impaired, which would also manifest as a sensation of AH (78). Even anxiety stemming from mask-wearing has been identified as a potential source of increased dyspnea (80), with it being hypothesized that these elevations are due to differences in central processing of afferent feedback (76). By parsing the many distinct sensations associated with dyspnea, further insight into the specific physiological source may be gained, especially with PFM use where multiple mechanisms are potentially at play.

2.2 Physiological, Perceptual, and Performance Effects of Mask Use During Exercise

A recent meta-analysis has provided the clearest evidence of how a PFM worn during exercise affects the physiological, perceptual, and performance-related factors of exercise concurrently (5). Previous reviews did not parse different exercise intensities (8), however, Zheng et al. (5) described and compared the responses experienced during steady-state exercise to those experienced at termination of a graded exercise test ($_{END}$GXT). Despite this, most studies included investigated exercise with either N95/FFP2 (n=20) and/or surgical masks (n=36), and thus our understanding of the integrative nature of the exercise response to wearing an ESFM is limited. Additionally, analyses were grouped based on either exercise intensity or mask type and therefore fail to provide insight into the interaction between these two factors. Regardless, substantial insight into responses to PFM use during maximal and submaximal intensity exercise can be gained.

For all physiological measures apart from HR, significant differences were observed at $_{END}$GXT, with $\dot{V}O_2$ (standard mean difference= −0.68), SpO_2 (-0.6%), and blood lactate (-1.06 mmol) being significantly reduced with a significant elevation in $P_{ET}CO_2$ (+4.15 mmHg) when a PFM was worn. These findings suggest that PFM use is limiting an individual's ability to reach their peak unmasked aerobic power. This physiological impact may also influence performance, with PFM use significantly impairing maximal exercise performance. When steady-state exercise with a PFM was analyzed, HR (+2.7 BPM) and $P_{ET}CO_2$ (+2.09 mmHg) were significantly elevated with $\dot{V}O_2$ and SpO_2 significantly reduced. The significant reduction in $\dot{V}O_2$ with PFM use during steady-state exercise is particularly curious, with source authors speculating that this difference may be attributable to reductions in alveolar ventilation stemming from PFM resistance (81). Indeed, Lassing and colleagues (81) found both alveolar ventilation and the difference in oxygen content between arterial and venous blood to be significantly reduced when a face mask was worn during continuous vigorous-intensity exercise, with cardiac output significantly increased. This finding should be interpreted with caution however as both these measures are derived through expired gas analysis and may be altered if expired gas is not fully collected, a potential limitation which is discussed further in Section 2.4. Furthermore, provided that only 3 studies contributed to this finding (5), more research is needed on the effect a PFM has on oxygen delivery and extraction during exercise.

A range of perceptual responses were analyzed by Zheng and colleagues (5). At $_{END}$GXT, RPE, dyspnea, thermal discomfort, and fatigue were all significantly elevated in comparison to the unmasked condition. In studies that assessed both RPE and performance during a graded exercise test (GXT), RPE was found to be elevated alongside decrements in exercise performance (82, 83). When submaximal exercise was analyzed at the same absolute workload, RPE, dyspnea, and thermal discomfort were all still significantly elevated when a PFM was worn. Dyspnea, fatigue, and thermal discomfort had the largest elevations when N95/FFP2 masks were worn when compared to surgical and cloth PFMs.

Respiratory dynamics within exercise showed a significant reduction in both V_T (-210 ml) and $\dot{V}_E$ (-18.11 L) at $_{END}$GXT when a PFM was worn, with no change at the same absolute steady-state workload in the PFM conditions. The mean reduction in respiratory rate was not significantly different for steady-state exercise (-0.26 breaths/min) or at $_{END}$GXT (-1.4 breaths/min). There are several possible explanations for the reduction of both $\dot{V}_E$ and V_T observed during peak exercise with a PFM. One possible explanation is that reductions in ventilation are attributable to performance differences between conditions, with the highest attained workload being lower when a PFM is used. Zheng et al. (5) did indeed find exercise performance in a GXT was significantly reduced with a PFM (SMD= -0.34). Further to this, several papers included within the meta-analysis showed concurrent reductions in $\dot{V}_E$ and performance, although neither reported V_T (84, 85). Alternatively, Zheng et al. (5) proposed these significant reductions in ventilation at peak exercise may also be due to expired air leaking out of the metabolic collection mask and therefore not being analyzed, an issue that is discussed further in Section 2.4. Ultimately, due to the methodological challenges associated with expired gas collection in this context, findings pertaining to ventilatory responses should be interpreted with caution.

2.3 Unique Considerations for Aerobically Fit Individuals & Athletes

When it comes to wearing a face covering during exercise, it is important to interpret research findings in relation to the population being examined (6). Athletes can reach and maintain a much higher peak $\dot{V}_E$ than the general public (+20%) (86) and therefore aerobically fit individuals may experience elevated physiological and perceptual responses while wearing a mask when compared to healthy individuals at near-maximal exercise intensities. This is due to a high level of cardiovascular fitness which may meet or even exceed the capacity of the respiratory system in some cases (23). This means that trained athletes, particularly those undertaking endurance sports, are often working very close to or potentially at the physiological limits of their respiratory system during high-intensity exercise (23). Research by Guenette and colleagues (87) found that 90% of female and 43% of male endurance-trained athletes assessed had an expiratory flow limitation at peak exercise, with elevated prevalence in females being partially attributable to smaller airways (so-called dysanapsis). This would suggest that any intervention that introduces respiratory resistance, such as the use of a PFM, may further exacerbate this respiratory limitation, with expiratory flow limitation becoming more likely due to a 'shrunken' maximal flow-volume envelope (88). To this point, data from Prado et al. (6) showed that the use of a PFM during exercise by a recreational male runner led to decreases in peak inspiratory and expiratory flows and ultimately an inspiratory flow limitation at peak exercise with a PFM, an occurrence absent in the unmasked condition. Furthermore, additional research has demonstrated impaired respiratory function with the use of a PFM, manifesting as a reduction in peak and forced expiratory flow measures (42, 81).

The expedited onset of the respiratory muscle metaboreflex is another potential area where athletes may be differentially impacted by mask-wearing. Given the ability of athletes and fit individuals to reach and sustain a significantly higher $\dot{V}_E$ when compared to the general population, the elevated inspiratory and expiratory WOB can lead to accelerated respiratory muscle fatigue when sustained exercise over 80% $\dot{V}O_2$ max is performed (23). Increased respiratory muscle activation required to breathe with added airflow resistance has the potential to further exacerbate this response, potentially bringing about the respiratory muscle metaboreflex sooner or at a lower exercise intensity, although no literature to my knowledge has examined the onset of this response in the context of exercise with a PFM.

It is widely accepted that athletes are at a higher risk of EIB, with the burden of conditioning high volumes of air over months and years of training being linked to airway hyperresponsiveness (56). Definitionally, EIB manifests as a ≥10% decrease in forced expiratory volume in 1 second (FEV_1) following exercise (13). Other commonly used spirometry measures are often also reduced in EIB including peak expiratory flow (PEF) (89) and mid-expiratory flow measures (FEF_{25-75} & FEF_{50}) (90), although proposed thresholds for these measures are larger at >17.5% and >26.0% reduction from baseline respectively (91). In cases of EIB, spirometry reflects a restricted maximal flow-volume envelope, indicating impaired maximal airflow capacity (92). Although the assessment of EIB typically involves exclusively pre- and post-exercise measures, research has shown that functional reductions can occur during exercise in some individuals. Work by Van Leeuwen and colleagues (93) found that 63% of asthmatic children positive for EIB experienced a reduction in lung function during treadmill exercise at 80% maximum HR, with the average time to EIB being 7.75 minutes. Termed breakthrough EIB, this phenomenon, although well documented in asthmatics, has not been studied thoroughly in non-asthmatics with EIB. Research by Rundell et al. (15) found breakthrough EIB in 5/9 cross-country skiers with EIB during a mock cross-country ski race lasting roughly 1 hour, with a sustained HR of over 90% maximum. Additionally, a case study of a wilderness multisport endurance athlete demonstrated a 25% reduction in FEV_1 during an 8.5-hour race, despite normal baseline spirometry (94). Provided that limited research has been conducted on the intra-exercise respiratory responses in fit individuals, it remains unclear whether the use of an ESFM would help to acutely preserve respiratory function.

Although there is a paucity of literature examining the impact of PFMs worn during exercise in aerobically fit individuals, the few papers that do exist shed light on potential PFM-induced differences in athletic and aerobically fit populations. A study of 16 endurance-trained athletes undertaking GXTs on a cycle ergometer found significant reductions in maximal exercise performance and $\dot{V}O_2$ max for both surgical and FFP2 masks when compared to an unmasked control condition (84). All participants cycled >6 hours per week, had an anaerobic threshold of >200 watts, and a maximal aerobic power of >4.6 watts per kg body mass. The study also reported that most participants reported increased dyspnea at termination of the surgical mask condition, which was subjectively attributed to the soaking and deformation of the mask which resulted in the mask clinging to the participant's face. This was not observed in the FFP2 mask condition due to the increased mask rigidity. Excess dyspnea associated with surgical mask saturation was not observed in studies of healthy, non-athletes exercising with surgical masks (95) underlining the importance of specific inquiry into fit populations. Egger et al. (84) attributed this difference between athletic and healthy populations to elevated $\dot{V}_E$ and increased moisture retention associated with higher absolute exercise intensities. Comparisons of these two papers should be made with caution, however, as only Egger et al. (84) opted to collect metabolic data and thus utilized a 'double mask' arrangement, which may have artificially accelerated mask moisture absorption.

Research in female endurance athletes may further illuminate some of the previous findings. Rojo-Tirado and colleagues (45) performed a comparison of spirometry and physiological measures during graded treadmill exercise between unmasked, ESFM, and FFP2 mask conditions, finding that the FFP2 mask significantly impaired respiratory function and exercise performance over the unmasked condition. Interestingly, the ESFM used in the trial (Emotion Face Mask, Mascarillas, Toledo, Spain) resulted in physiological and respiratory responses not significantly different from the control condition, with no significant differences in $\dot{V}O_2$ max, V_T, $\dot{V}_E$, or time to exhaustion between the two. Furthermore, any resistance imposed by this mask was not enough to significantly impact the resting spirometry maximal flow-volume envelope when compared to the unmasked control. The ESFM assessed in this study may not be representative, however, provided its materials and construction resemble a loose mesh. This lack of resistance to flow may unfortunately come at the expense of viral protection, as flow resistance is a key characteristic of PFMs for mitigating aerosol transmission (96). These findings are supported by pilot work by Segimoto and colleagues (97), who found no differences in peak V_T or $\dot{V}O_2$ max in 7 varsity athletes when an ESFM was used.

Only one other study was identified that examined the impact of ESFM use. When the physiological and perceptual responses of 12 active individuals undertaking 60 minutes of walking and jogging (35% - 60% $\dot{V}O_2$ max) in a hot environment (32°C, 54% RH) were analyzed, no significant differences in HR or rectal temperature were found when surgical, N95, gaiter, and ESFMs were compared (61). When perceptual responses were investigated, RPE, thermal sensation, thirst, and fatigue were not significantly different when a PFM was worn, although PFM use was found to significantly elevate breathing discomfort (BD)(61). Given that work by Rojo-Tirado et al. (45) and Yoshihara et al. (61) was the only published literature identified that examined a mask specifically designed for exercise, more research is needed on ESFMs.

2.4 Methodological Critiques of Existing Mask Research

The methodology used by many researchers when looking into the physiological and perceptual consequences of mask-wearing may not just limit external validity, but also internal validity. Many studies examining the influence of PFMs during exercise including work by Prado et al. (24), Rojo-Tirado et al. (45), Egger et al. (84), and Fikenzer et al. (42) performed data collection using a 'double-masked' arrangement, where a metabolic collection mask is placed over top of the protective mask being studied. This setup, although providing researchers with the ability to collect metabolic data during exercise with a PFM, limits the external validity of such a study as 'double masking' in this fashion is not indicative of real-world use and may inadvertently alter PFM function (6). It also may accelerate the mask's absorption of expired moisture which has been shown to increase resistance during extended use of N95 respirators at low ventilatory rates (98), a process that is likely to be hastened at respiratory rates experienced during vigorous to maximal intensity exercise. These dynamic resistance changes may also impact an individual's perception of effort, with expiratory flow resistance being shown to cause excess dyspnea (99), which may lead an athlete to terminate exercise sooner. In these cases, it may be difficult to parse whether any physiological, performance, and/or perceptual differences are being driven solely by the protective mask or by the combination of the two. Therefore, to truly assess the responses to mask-wearing in aerobically fit individuals, it may be necessary to forgo metabolic data collection by focussing on non–obtrusive measures that allow physiological data to be collected, better representing real-world responses to mask use during exercise.

Another potential limitation associated with this method of data collection is the considerable risk of leakage due to a poor seal around the face. For ventilatory and metabolic parameters to be assessed accurately during exercise, all expired gas must be directed through the central port of the metabolic mask. If leakage were to occur, this has the potential to artificially deflate measures derived from respiratory flow including $\dot{V}_E$, V_T, expiratory flow rates, $\dot{V}CO_2$, and $\dot{V}O_2$. Given the gasket of the metabolic collection mask is designed to sit directly on top of the skin, the introduction of a PFM has the potential to impact the airtight nature of this seal, a potential problem the has been noted by other researchers in the field (5, 8). Although many authors report checking for seal at rest (24, 42, 84, 100), leaks may develop during the high respiratory flow rates and movement associated with vigorous exercise, where they may not be readily detected. Provided much of the existing research in this area has used methodology like that outlined above, it is worth critically evaluating the validity of their claims regarding responses associated with mask use.

2.5 Rationale

Although previous research has examined how surgical, N95, cloth, and heat & moisture exchange masks impact responses to exercise, limited research has been conducted on the use of ESFMs. Furthermore, although existing studies pertaining to PFM use during exercise have sampled from a wide range of populations including individuals with chronic obstructive pulmonary disease (101), coronary artery disease (102), and healthy (81), few studies exist that empirically analyze ESFM use in aerobically fit individuals (45). The methodological choices in some of the existing literature on PFMs may also make generalizations to real-world mask use difficult, and in some cases may undermine findings entirely. To make informed recommendations concerning mask use, PFM use must be contextualized through mask type, activity parameters, and population considerations.

Provided that prior research has collectively shown the potential for face coverings to limit exercise performance (5), fit individuals may experience an even larger performance reduction given their elevated respiratory demands achieved at peak exercise. However, given that EIB is more prevalent in fit individuals who partake in endurance and other high-ventilation sports (103), the use of a simple face covering in athletes may allow for fit individuals to delay the onset or reduce the severity of respiratory function reductions associated with EIB. With these issues and gaps in the literature, we aimed to answer the following questions:

a) Does an ESFM alter the physiological or perceptual responses to submaximal intensity exercise in aerobically fit individuals accustomed to hard exercise?
b) Does an ESFM alter the physiological or perceptual responses to maximal intensity exercise in aerobically fit individuals accustomed to hard exercise?

c) Does an ESFM alter the incidence or severity of within-exercise respiratory function reductions in aerobically fit individuals with and without EIB?

d) Does an ESFM alter maximal exercise performance in aerobically fit individuals accustomed to hard exercise?

2.6 Hypotheses

Several hypotheses were formulated to examine the impact of ESFM use during exercise. These hypotheses were based on theoretical mechanisms and previous research reviewed in Section 2.

a) Submaximal-Intensity Exercise:

- *Hypothesis: ESFM use would elevate perceptual measures without physiological changes.*
- *Physiological measures (HR, f, SpO_2) would remain unchanged.*
- *Perceptual measures (RPE, BD, $_P$WOB, AH) would increase with higher exercise intensity.*
- *CT and throat tightness (TT) would decrease due to reduced osmotic stress.*
- *Leg discomfort (LD) would not be significantly affected.*

b) Maximal-Intensity Exercise:

- *Hypothesis: ESFM use would elevate perceptual measures without physiological changes.*
- *Physiological measures (HR, f, SpO_2) would remain unchanged.*
- *Perceptual measures (RPE, BD, $_P$WOB, AH) would increase at peak exercise.*
- *CT and TT would decrease due to reduced osmotic stress.*
- *LD would not be significantly affected.*

c) Respiratory Function:

- *Hypothesis: ESFM use would attenuate reductions in respiratory function during exercise.*
- *Spirometry measures sensitive to differences in airway caliber (FEV_1, PEF, FEF_{25-75}, FEF_{50}) would show improvement with ESFM use.*
- *Hyperresponsive individuals would benefit the most from ESFM use.*

d) Exercise Performance:

- *Hypothesis: ESFM use would impair exercise performance.*
- *ESFM use would shorten time to exhaustion.*

These hypotheses were formulated to guide the investigation into the effects of ESFM use on various aspects of exercise.

Chapter 3: Research Study

Abstract

Introduction: The impact of masks marketed for "exercise use" (ESFM) in aerobically fit individuals on physiological, perceptual, respiratory, and performance responses is inconclusive. Furthermore, the potential benefits of these masks in mitigating exercise-induced bronchoconstriction (EIB) in this population are unknown.

Objective: To assess the effects of an ESFM on physiological, perceptual, respiratory, and performance measures during submaximal and maximal-intensity exercise in aerobically fit individuals. Hypotheses predicted elevated perceptual burden without physiological changes, impaired performance, and preserved respiratory function in individuals with EIB.

Methods: Twenty-four individuals (11 female) completed a discontinuous graded exercise test on a treadmill under two conditions (ESFM and Control). Physiological measures, respiratory function measures, and perceptual measures were assessed. Performance was determined by time to exhaustion. Statistical analyses included linear mixed modeling, repeated measures analysis of variance, and pairwise comparisons using an alpha value of 0.05.

Results: ESFM use significantly impaired performance (median = -150.5 s) and decreased SpO_2 at maximal intensity (-3.7%). Perceptions of air hunger and work of breathing were elevated across submaximal and maximal intensities. RPE and breathing discomfort were significantly elevated submaximally but not maximally. Spirometry measures were not significantly different at termination but were significantly improved at submaximal intensities in participants with and without EIB.

Conclusion: ESFM use in fit individuals increased perceptual discomfort, impaired performance, and augmented arterial desaturation. Respiratory function improvements were observed but were accompanied by adverse perceptual sensations. Despite improvements in respiratory function, elevated perceptual burden and decreased exercise performance may limit the real-world utility of ESFMs for athletes.

3.1 Introduction

As the use of a protective face mask (PFM) was recommended in public settings to mitigate the spread of Severe Acute Respiratory Syndrome Coronavirus 2 during the COVID-19 pandemic, research emerged attempting to elucidate the potential effects of PFM use during exercise. Collectively, understanding of a PFM's influence on physiological and perceptual responses during exercise is much improved, where a PFM may acutely modify cardiorespiratory and perceptual responses, with little risk to health during exercise (6). However, the extent to which physiological parameters are modified during exercise remains disputed, with conflicting findings in recent studies (5). The heterogeneity in research findings is likely due to differences in mask type, participant characteristics, exercise modality and intensity, as well as environmental characteristics (6). Studies that have evaluated metabolic responses via indirect calorimetry, although insightful, also likely impair our ability to understand the real-world responses to PFM use during exercise (42, 45, 84). This is due to a 'double masked' arrangement (metabolic collection mask secured over top of the PFM being assessed), which may have confounded measurements of breathing dynamics (104) and enhanced perceptual discomfort beyond the contribution of the PFM alone.

All PFMs impose a combination of added breathing resistance and ventilatory dead space (VD) and the degree to which they do this varies between different types of PFMs (16). These factors likely impact ventilatory and cardiopulmonary responses to exercise by increasing expired air rebreathing and elevating breathing resistance (6, 16). Additionally, these factors may influence one's rating of perceived exertion (RPE) and/or dyspnea during exercise, which may in turn have a detrimental impact on exercise tolerance and performance (105). Although the influence may be negligible at rest or during light physical activity (106), the elevated metabolic demands associated with vigorous-intensity physical activity may accentuate the physiological and perceptual burden. For aerobically fit individuals, whose high level of cardiovascular fitness coincides with heightened ventilatory demands (23), this influence is likely magnified. Given work of breathing increases exponentially with increased exercise intensity and associated ventilation (107), athletes and other aerobically fit individuals may experience elevated physiological and perceptual responses during exercise, especially during high-intensity activity.

Exercise-specific face masks (ESFMs) are a specific type of PFM that boast low resistance to flow and suitability for exercise across a range of intensities (108). Given the properties of these PFMs differ significantly from clinical PFMs such as surgical and N95 masks, their influence on physiological and perceptual responses may differ as well. Although claims surrounding their acceptability across a spectrum of exercise intensities have been made, few studies have been conducted assessing PFMs designed specifically for exercise (45, 61). Thus, it remains unclear if ESFMs impose a substantial physiological and/or perceptual burden, particularly in aerobically fit individuals exercising at submaximal and maximal intensities.

Although PFMs are traditionally perceived to have predominantly negative or neutral effects when associated with exercise (105), covering the mouth and nose supports the heating and humidification of inspired air, potentially attenuating exercise-induced bronchoconstriction (EIB) (11). This is because dry air hyperpnea during exercise is the primary stimulus for EIB (55), and an ESFM may help to protect against airway desiccation when exercising in dry environments, leading to less airway narrowing post-exercise, especially in individuals with airway hyperresponsiveness (109). This attenuated post-exercise bronchoconstriction has been demonstrated by using a scarf worn over the mouth (14) or surgical mask (109) however, within-session changes in respiratory function during prolonged exercise have not been well investigated. There is also limited evidence to suggest that some individuals who exhibit post-exercise reductions in respiratory function will also do so during intense, prolonged exercise, often referred to as breakthrough EIB (15, 93). It is therefore not known whether an ESFM modifies acute within-exercise airway responses to aerobic exercise in those with and without EIB.

Limited research has been conducted on the responses to ESFM use during exercise. Furthermore, previous research using a double mask arrangement lacks a degree of external validity, potentially confounding the true perceptual, physiological, and performance outcomes to exercise with a PFM. Finally, the within-exercise influence of a face covering on respiratory function in individuals where exercise hyperpnea increases the risk of bronchoconstriction is unknown. Thus, this study aimed to determine if the use of an ESFM in aerobically fit individuals accustomed to intense exercise significantly altered within exercise physiological, perceptual, respiratory, or performance responses to graded treadmill exercise. It was hypothesized that the use of an ESFM would increase the within-exercise perceptual burden without influencing physiological responses to a given exercise intensity, impairing peak exercise performance. Additionally, we hypothesized that the use of an ESFM would help to maintain within-exercise respiratory function in individuals prone to changes in airway caliber, especially those with EIB.

3.2 Methods

Participants

Twenty-four aerobically fit individuals (11 females) were recruited for this study. This sample size exceeded that required for 80% power, with an alpha=0.05 and a standard mean difference of 0.60, as calculated in GPower software based on a T-distribution (n=19) (GPower 3.1.9.7, Kiel, Germany). This effect size was estimated based on a meta-analysis by Shaw et al. (8), who found standard mean differences for dyspnea of +0.60 when a PFM was worn during exercise. Thus, a sample size of >20 provided sufficient power to observe any differences in the primary outcome measure of dyspnea.

Aerobically fit individuals between the ages of 18 and 40 with a minimum of 3 years of regular aerobic exercise training were recruited. This aerobic exercise could take the form of recreational running, formal endurance sport training, or as part of a team sport. Participants also were required to be running regularly at the time of data collection. Given older athletes remain competitive with appreciable aerobic power later in their career (110), recruitment across a wide range of ages was justified. Participants were also free of any chronic respiratory or musculoskeletal conditions that may have adversely impacted participation in a graded running protocol. Participants that experienced exercise-related reductions in respiratory function but were otherwise healthy were included, as EIB is known to affect a high proportion of athletes (52). Participants were recruited via convenience sampling of existing networks maintained by the primary investigator and other researchers within the Athlete Health Lab. Participants were asked to contact the primary investigator via email, at which point it was verified that they met the inclusion criteria.

Design Overview

This study was a within-subjects, crossover, repeated measures design. Upon arrival to their first trial, participants were randomly assigned into 1 of 2 experimental conditions via a coin flip to determine the order in which they completed the two exercise conditions (either masked-unmasked or unmasked-masked). This randomization resulted in 13 participants experiencing the masked condition first and 11 the unmasked condition. The standardized ESFM used in this study was manufactured by Outdoor Research (Adrenaline Sports Face Cover Kit, Outdoor Research, Seattle, USA) and was specifically marketed for use during "high-exertion workouts and labor-intensive activities" (108). The mask is constructed out of 100% polyester and includes both a wire nose bridge and adjustable ear loops (108). As per manufacturer instructions, the ESFM was used with the included disposable filter, which was secured with safety pins to prevent the filter from shifting during the exercise trial (Figure 1). An unused mask and filter assembly was provided to participants immediately prior to their masked condition. Although Outdoor Research does not explicitly report mask resistance, they do report a particulate filtration efficiency of 95% when the included filter is used (108). Additionally, private laboratory testing of a similar mask manufactured by Outdoor Research which uses the same disposable filter reported a resistance of 0.43 cmH_2O at a continuous flow rate of 85L/min (111). When contextualized via the ASTM standards for barrier (non-medical) face coverings, this mask would likely be categorized as a Level II (higher performance) face covering both in terms of resistance and filtration efficiency, with a filtration efficiency of ≥50% and resistance ≤0.5 cmH_2O (22). A minimum of 72 hours between exercise tests was maintained to mitigate the risk of residual fatigue impacting subsequent testing sessions.

The exercise assessment protocol consisted of a graded exercise test (GXT) performed on a treadmill (FMTK72509 Incline Trainer, Freemotion Fitness, Logan, USA). The test consisted of up to nine, 5-minute stages, each performed at a constant velocity. The treadmill velocity for the first stage was set to replicate a running pace of 7:00 minutes per kilometer (min/km). For each subsequent stage, the pace was increased by 0:30

min/km until volitional exhaustion was reached, with the gradient being held constant at 1% to replicate the energetic cost associated with overground running (112) (Table 1). Subjective and respiratory function measures were taken between each consecutive stage, necessitating a brief standing rest period between stages. The experimental procedure for each condition was identical, with face covering (or lack there of) used during the exercise protocol manipulated. All exercise testing was conducted in an indoor, climate-controlled exercise laboratory, where the temperature and humidity were held constant with an ambient temperature of 19-20°C and estimated absolute humidity of 2-8 mg H_2O/L of air. These environmental conditions are considered typical for indoor exercise (48) and have previously been identified as adequate for the provocation of EIB, with an absolute humidity of less than 10 mg H_2O/L (49).

Table 1. Graded exercise test protocol.

Stage	Simulated Pace (min/km)	Treadmill Velocity (Mph)	Gradient (%)	Stage Distance (m)
Stage 1	7:00	5.3	1	711
Stage 2	6:30	5.7	1	764
Stage 3	6:00	6.2	1	831
Stage 4	5:30	6.8	1	912
Stage 5	5:00	7.5	1	1006
Stage 6	4:30	8.3	1	1113
Stage 7	4:00	9.3	1	1247
Stage 8	3:30	10.7	1	1435
Stage 9	3:00	12.0	1	1609

Figure 1. Outdoor Research Adrenaline Face Mask. For all exercise testing, the included disposable filter was secured to the inside of the ESFM with safety pins.

Preparation.

Prior to their designated testing day, participants were sent an information package via email, which included a copy of the informed consent, a background questionnaire, and pre-trial instructions. The background questionnaire consisted of items derived from Kennedy et al. (113) and was aimed at assessing common triggers for respiratory symptoms, existing respiratory conditions, training history, and commonly experienced respiratory symptoms. This provided an indication of the participant's level of athletic experience as well as typical respiratory responses to exercise. Pre-trial instructions included refraining from any form of exercise, caffeine, or alcohol on the day of the trial. Additionally, participants on any medications that could influence lung function were instructed not to take these prior to testing (24 hours for short-acting β2-agonists and 72 hours for inhaled corticosteroids and long-acting β2-agonists) (114). This enabled us to see any potential impact the mask may have had on attenuating exercise-provoked reductions in airway function during the exercise bout.

Graded exercise assessment.

Upon arrival at the laboratory, participants were required to complete the Canadian Society for Exercise Physiology 'Get Active' Questionnaire to ensure they could safely undertake exercise (115). Once complete, the participant's chest circumference was measured to determine the optimal size of the vest which allowed for continuous monitoring of heart rate (HR) and breathing frequency (*f*) during the GXT (EqO2+ LifeMonitor, Equivital, New York, USA). Data was wirelessly streamed to and recorded in electronic charting software (LabChart 8, ADInstruments, Colorado Springs, USA). Once the vest was properly fitted, several measures were assessed before the start of the exercise protocol. These included fractional exhaled nitric oxide (FeNO), breathing discomfort (BD), chest tightness (CT), throat tightness (TT), leg discomfort (LD), air hunger (AH), perceived work of breathing ($_P$WOB), rating of perceived exertion (RPE), and spirometry. Baseline spirometry was assessed following American Thoracic Society guidelines, which dictate that expiratory forced vital capacity (FVC) maneuvers are to be repeated until FVC and FEV_1 values are repeatable (within 150 ml), up to a maximum of 8 attempts (116). Once baseline measures were completed, a pulse oximetry sensor (Nellcor SpO_2 Forehead Sensor, Medtronic, Minneapolis, USA) was affixed above the left eyebrow which allowed for continuous monitoring of arterial oxygen saturation (SpO_2) during the GXT. Following this, the participant was briefed by one of the research team members on the GXT protocol.

At the start of each test, the participant was instructed to stand on the treadmill rails while it was brought up to the velocity of the first stage (5.3 mph, 1% gradient). Once at speed, the participant was asked to carefully 'skate' onto the treadmill surface at which point a timer was started. Upon completion of the 5-minute stage, participants were instructed to return to the rails of the treadmill at which point the treadmill was stopped. BD, CT, TT, LD, AH, $_P$WOB, and RPE were re-assessed in a standing position via laminated copies placed in front of the participant. Between-stage assessment of these subjective measures allowed for both submaximal and maximal responses to be assessed using a single exercise protocol. Following the administration of these subjective measures, spirometry was also assessed in a standing position via a single expiratory FVC maneuver. This test was performed upright and without repeated measures as it was preferable that the rest interval between stages be kept to a minimum. After between-stage measures were taken, the participant was instructed to place their feet back on the rails before the treadmill was brought back to the velocity prescribed for the next stage. The rest period between consecutive stages was between 30 and 60 seconds. This cycle continued until either a) the participant reached volitional exhaustion or b) completed all 9 stages of the exercise protocol. Strong verbal encouragement was provided by research staff throughout the graded exercise assessment to ensure maximal effort from participants in all trials. Immediately after termination, regardless of stage completion, one final set of exercise measures was taken before entering the follow-up phase.

Post-exercise.

Immediately following exercise termination, the follow-up phase of the protocol began. The participant was free to walk around to cool-down prior to their first follow-up FVC maneuver which took place at 3 minutes post-exercise. These spirometry measures were conducted as per the same methodology used for baseline data collection and were repeated at 3, 6, 10, 15, 20, and 30 minutes post-exercise. At each time point, up to 3 FVC maneuvers were performed to ensure values obtained were repeatable. This extended measurement period was necessary to detect the maximal reduction in FEV_1 from baseline values, which is the standard diagnostic measure for the identification of EIB that typically peaks within 30 minutes post-exercise provocation (13). Finally, session RPE was assessed on a Borg CR-10 scale (117).

Measures

Physiological measures.

Both HR and *f* were continuously monitored during exercise using an Equivital monitoring vest streamed wirelessly into electronic charting software. This system was minimally obtrusive and was intended not to have any confounding impact on movement or exercise performance during the exercise test. HR was derived from 2-lead electrocardiogram data recorded via surface electrodes built into the vest. HR was then calculated via the frequency of QRS complexes. *f* was derived from the Equivital's respiratory belt, which provides a continuous tracing proportional to changes in chest diameter. *f* was then calculated by the frequency of respiratory cycles, which were delineated based on cyclical peaks in chest expansion and were expressed in breaths per minute.

SpO_2 was assessed via a Nellcor pulse oximeter (Nellcor N-600x, Medtronic, Minneapolis, USA) utilizing a forehead probe affixed above the left eyebrow. The use of a forehead probe as opposed to the more commonly used finger probe was chosen to mitigate both the risk of motion artifact associated with running and the potential of poor peripheral perfusion in the hands (118). The SpO_2 reading was collected continuously and recorded in LabChart via the analog signal output of the Nellcor unit routed through an analog data acquisition system (Powerlab, ADInstruments, Colorado Springs, USA). The Nellcor analog output was calibrated prior to each test to ensure the accuracy of the analog signal.

Perceptual measures.

Perceptual measures were recorded on a paper data sheet both at rest, following each stage of the GXT, and following exercise termination. The Dalhousie Dyspnea Scales (119) assessed respiratory sensations, which is a tool that contains 4 items, each rated on a 7-point pictorial scale (Appendix A). Participants were asked to indicate how their a) breathing, b) chest, c) throat, and d) legs felt by pointing to the images contained with in the scale. Second, a scale was used to assess the participant's AH and $_P$WOB (120). This 7-point scale consists of verbal cues ranging from 'None' (1) to 'Extreme' (7). Participants were taught to differentiate the two respiratory sensations, as defined by statements included in the tool, before obtaining baseline measurements (Appendix B). Finally, the Borg RPE scale (117) assessed global perception of exertion on a 15-point scale. The administration of these scales provided a wholistic evaluation of perceptual experiences associated with each condition across the entire range of intensities.

Following each running trial, participants were asked to rate their session RPE on the Borg CR-10 scale (117), which provided a global indication of perceived exertion during the entirety of the exercise trial.

Respiratory measures.

Respiratory measures consisted of forced vital capacity (FVC) maneuvers using a portable spirometer (Spirodoc, MIR, Roma, Italy). Single-use, factory-calibrated turbines were used to mitigate the risk of biohazardous contamination associated with this expiratory maneuver. The participants were instructed to complete a forced vital capacity maneuver based on American Thoracic Society guidelines for spirometry (116). Several standard respiratory function measures were automatically outputted following the completion of each maneuver including FEV_1, FVC, FEV_1/FVC, PEF, FEF_{25-75}, and FEF_{50}.

Several FVC maneuvers were performed before exercise to obtain a pre-exercise baseline. FeNO was also measured (NIOX VERO, Circassia, Oxford, UK) before exercise to assess each participant's baseline airway inflammation (121).

During the exercise protocol, FVC maneuvers were performed in a standing position following the completion of each stage of the GXT. To determine the EIB status of participants, spirometry was also performed serially following the graded exercise assessment. Maneuvers were performed in triplicate at 3, 6, 10, 15, 20, and 30 minutes' post-exercise. The highest FEV_1 from each timepoint was included in analysis, with a ≥ 10% post-exercise reduction from baseline indicating EIB (13), allowing for sub-analyses to be performed to determine if ESFM use had a differential impact on respiratory measures taken during exercise in individuals with EIB (EIB+) versus those without (EIB-).

Performance measures.

Test performance was assessed first by recording the last stage completed in full during the GXT in both conditions. Time to exhaustion was also assessed in both exercise conditions, calculated as:

*Tine to Exhaustion (s) = (Stages completed * 300) + time to failure in the incomplete stage (s), if applicable*.

The exclusion of resting periods in this calculation ensured that any slight variance in the time allotted for the between-stage assessment did not impact time to exhaustion.

Analysis

All analyses for this research project were conducted in SPSS Statistics (SPSS Statistics 28, IBM, Armonk, USA) using an alpha value of 0.05 as a threshold for indicating significant differences.

Submaximal physiological and perceptual responses were assessed across several discrete exercise intensities. The final stage completed under both experimental conditions for each subject was designated their 'peak equivalent velocity'. Subsequently, stages approximating 70%, 80%, and 90% of this velocity were identified for each participant and were included in analyses of submaximal responses. Physiological measures averaged over the final 30 seconds of each stage were used to indicate the physiological responses to each intensity. Perceptual measures collected immediately following the completion of each stage indicated submaximal perceptual responses.

A mixed linear model was applied to subjective and physiological measures assessed at numerous submaximal exercise intensities during the GXT (condition X submaximal intensity). These included HR, *f*, SpO_2, CT, TT, LD, BD, $_P$WOB, AH, and RPE. The model consisted of random intercepts with fixed slopes. The fixed effects examined included condition and exercise intensity, with participants being treated as a random effect to parse errors associated with inter-individual variance. The main effects of each of the fixed effects were assessed in addition to their interaction. For significant interactions, pairwise comparisons for each exercise intensity were used to compare masked and unmasked exercise conditions.

Maximal responses were also examined via perceptual and physiological measures assessed at exercise termination. For perceptual responses, scales administered immediately following participant termination under each condition were used to indicate peak responses. For physiological measures, the 30 seconds preceding exercise termination was averaged to assess maximal responses. Depending on individual performance on each exercise test, the running pace at which peak responses were assessed was not necessarily the same between experimental conditions. For physiological and perceptual measures, differences across conditions were assessed via a paired-sample T-test. Normality was assessed using a Shapiro-Wilk test. If the assumption of normality was violated or outliers were present, either a Wilcoxon-Rank Sign Test or a Sign test was utilized as an alternative non-parametric, pairwise comparison, depending on the distribution of differences [Laerd Statistics, 2023].

To account for daily changes in lung function and to normalize across individuals with different lung sizes, all values derived from spirometry were analyzed as a delta percentage of pre-exercise baseline. These included FEV_1, FVC, FEV_1/FVC, PEF, FEF_{25-75}, and FEF_{50}. For submaximal respiratory responses, all stages from the start of the GXT protocol until the point of substantial data attrition due to participant dropout were analyzed via a repeated measures analysis of variance. The main effects were assessed in addition to their interaction. For significant interactions, pairwise comparisons for each exercise intensity were used to compare masked and unmasked exercise conditions. These analyses were conducted both on the entire sample and separately for EIB+ and EIB-participants. To examine respiratory responses to intense exercise, pairwise comparisons of spirometric values were made with both measures collected at termination and with measures collected at 100% peak equivalent velocity for each subject. Pairwise comparisons were conducted following the methodology previously outlined for physiological and perceptual measures. If a technically adequate spirometry maneuver could not be obtained for a given sub-maximal exercise intensity, the values from the previous FVC maneuver were carried forward.

Performance differences across conditions were assessed via a paired-sample T-test. This was performed for both time to exhaustion and the last stage completed for each exercise trial. Normality was assessed using a Shapiro-Wilk test. If the assumption of normality was violated or outliers were present, either a Wilcoxon-Rank Sign Test or a Sign test was utilized as an alternative non-parametric, pairwise comparison, depending on the distribution of differences.

3.3 Results

Descriptives

Descriptive variables are shown in Table 2. One participant was excluded from all spirometry analyses because they were unable to perform technically proficient FVC maneuvers in one of their experimental trials (n=23). This was indicated through visual inspection of flow-volume loops from their FVC maneuvers, with a bimodal expiratory flow tracing resulting in the spirometer being unable to compute FEV_1 at several timepoints during and proceeding the exercise trial. Of the remaining 23 participants, 3 were EIB+ under both experimental conditions (1 female), 2 were EIB+ in the masked condition only (1 female), and 1 was EIB+ in the control condition only (male). 17 participants (9 female) did not have a 10% or greater reduction in FEV_1 post-exercise under either condition. Baseline respiratory function was not significantly different between the two experimental conditions for any of the spirometry measures analyzed (Table 2).

Table 2. Subject Characteristics.

		Sex		EIB Status		
		Female (n=11)	Male (n=13)*	EIB+ (n=6)	EIB- (n=17)	Total (n=24)**
		mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)
	Age (years)	26 (7)	29 (8)	27 (7)	28 (8)	28 (8)
	Height (cm)	167 (7)	188 (7)	186 (12)	175 (12)	178 (13)
	Weight (kg)	62.4 (6.0)	81.5 (8.2)	73.6 (10.9)	69.9 (11.4)	71.9 (12.1)
	BMI (AU)	22.5 (2.8)	23.0 (1.9)	21.3 (0.9)	23.0 (2.4)	22.8 (2.4)
	Years of Competitive Endurance Sport	9 (6)	15 (7)	15 (5)	10 (8)	12 (7)
Control	**FeNO (PPB)**	14 (5)	63 (54)	74 (72)	27 (25)	40 (46)
	Post-exercise FEV_1 Nadir (% Δ)	-1.2 (7.3)	-5.8 (7.7)	-11.6 (9.8)	-0.8 (4.4)	-3.6 (7.7)
	FEV_1 (L)	3.42 (0.58)	5.11 (0.94)	4.78 (1.43)	4.14 (1.05)	4.30 (1.16)
	% pred	*99 (13)*	*100 (14)*	*97 (13)*	*101 (14)*	*100 (13)*
	FVC (L)	4.32 (0.66)	6.99 (1.68)	6.38 (1.94)	5.48 (1.84)	5.71 (1.86)
	% pred	*108 (14)*	*112 (25)*	*107 (19)*	*111 (21)*	*110 (20)*
	PEF (L/s)	7.16 (0.74)	9.92 (1.6)	9.23 (2.23)	8.38 (1.75)	8.60 (1.87)
	FEF_{25-75} (L/s)	3.41 (0.86)	4.35 (1.18)	4.70 (1.41)	3.62 (0.89)	3.90 (1.12)
	% pred	*87 (18)*	*86 (18)*	*94 (19)*	*83 (17)*	*86 (18)*
	FEF_{50} (L/s)	4.22 (1.20)	4.95 (1.19)	5.35 (1.37)	4.34 (1.09)	4.60 (1.23)
	FEV_1/FVC (%)	79.6 (9.8)	74.3 (7.7)	76.3 (12.9)	77.0 (7.7)	76.8 (9.0)
	% pred	*92 (10)*	*90 (9)*	*91 (14)*	*91 (8)*	*91 (10)*
ESFM	**FeNO (PPB)**	15 (7)	52 (41)	58 (55)	26 (20)	34 (35)
	Post-exercise FEV_1 Nadir (% Δ)	-0.6 (9.4)	-4.6 (9.4)	-14.5 (5.9)	+1.5 (6.3)	-2.7 (9.4)
	FEV_1 (L)	3.46 (0.60)	5.06 (1.08)	5.11 (1.62)	4.00 (0.88)	4.29 (1.19)
	% pred	*100 (13)*	*99 (16)*	*104 (19)*	*98 (13)*	*100 (14)*
	FVC (L)	4.32 (0.70)	6.86 (1.49)	6.47 (2.23)	5.35 (1.50)	5.64 (1.73)
	% pred	*108 (16)*	*110 (20)*	*108 (23)*	*109 (16)*	*109 (18)*
	PEF (L/s)	7.23 (0.98)	9.92 (1.63)	9.90 (2.34)	8.19 (1.58)	8.63 (1.91)
	FEF_{25-75} (L/s)	3.27 (0.90)	4.32 (1.57)	5.04 (1.97)	3.39 (0.80)	3.82 (1.38)
	% pred	*84 (20)*	*85 (25)*	*100 (28)*	*79 (18)*	*84 (22)*
	FEF_{50} (L/s)	3.80 (1.17)	4.86 (1.54)	5.36 (1.99)	4.00 (1.06)	4.36 (1.45)
	FEV_1/FVC (%)	80.0 (7.5)	74.5 (8.0)	80.4 (9.3)	76.0 (7.6)	77.1 (8.1)
	% pred	*93 (8)*	*90 (9)*	*96 (9)*	*90 (8)*	*92 (9)*

Notes. Predicted values derived from 2012 Global Lung Function Equations (122).

* n=12 for spirometry values. ** n=23 for spirometry values

No significant differences in baseline spirometry values between ESFM and control conditions (p>0.05).

Submaximal Physiological and Perceptual Responses

Due to technical issues with data collection equipment, SpO_2 data for two participants was excluded from analysis (n=22). Additionally, *f* data could not be obtained for two participants due to a poorly fitting Equivital monitoring vest (n=22).

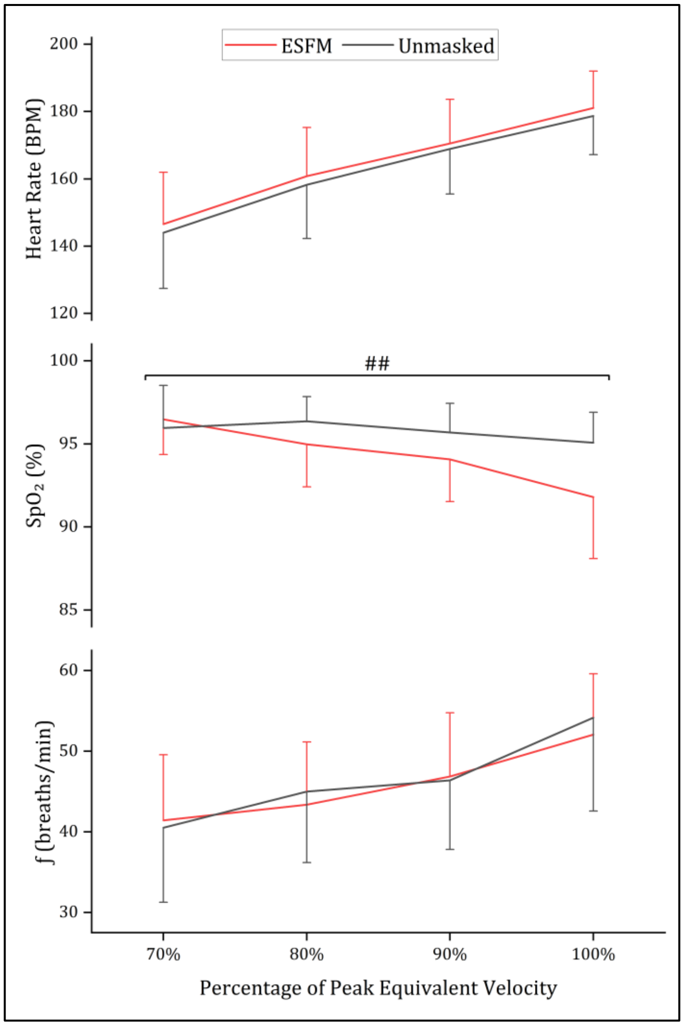

Figure 2. Mean (SD) physiological responses to treadmill running with (red) and without (gray) an ESFM.

Significant main effect (condition) and interaction effect (intensity x condition).

Use of an ESFM did not significantly alter submaximal HR, with no significant main effect of condition (+2.4 BPM, F=0.735, p=0.394) or interaction between intensity and condition (F=0.025, p=0.875) observed. Additionally, no significant differences in submaximal *f* were observed, with no main effect (-0.5 breaths/min, F=0.571, p=0.452) or interaction (F=1.298, p=0.259) present. When SpO_2 was analyzed, significant main (-1.2%, F=3.995, p=0.049) and interaction effects (F=16.141, P<0.001) were observed, with use of an ESFM significantly reducing arterial oxygen saturation. These differences became greater as exercise intensity approached maximum, with differences at 90%, 100%, and termination being significantly different.

An ESFM did not significantly alter the degree of LD, CT, TT, or AH during submaximal exercise compared to the unmasked condition. Although perceptual measures increased significantly with exercise intensity (p<0.001), the ESFM condition did not act to alter these responses when compared to the control condition (Figure 3). Use of an ESFM elevated several perceptual measures during submaximal exercise, with a significant main effect of condition being observed for RPE (+0.9, F=4.780, p=0.032), BD (+0.6, F=4.978, p=0.029) and $_P$WOB (+0.7, F=7.501, p=0.008) (Figure 3).

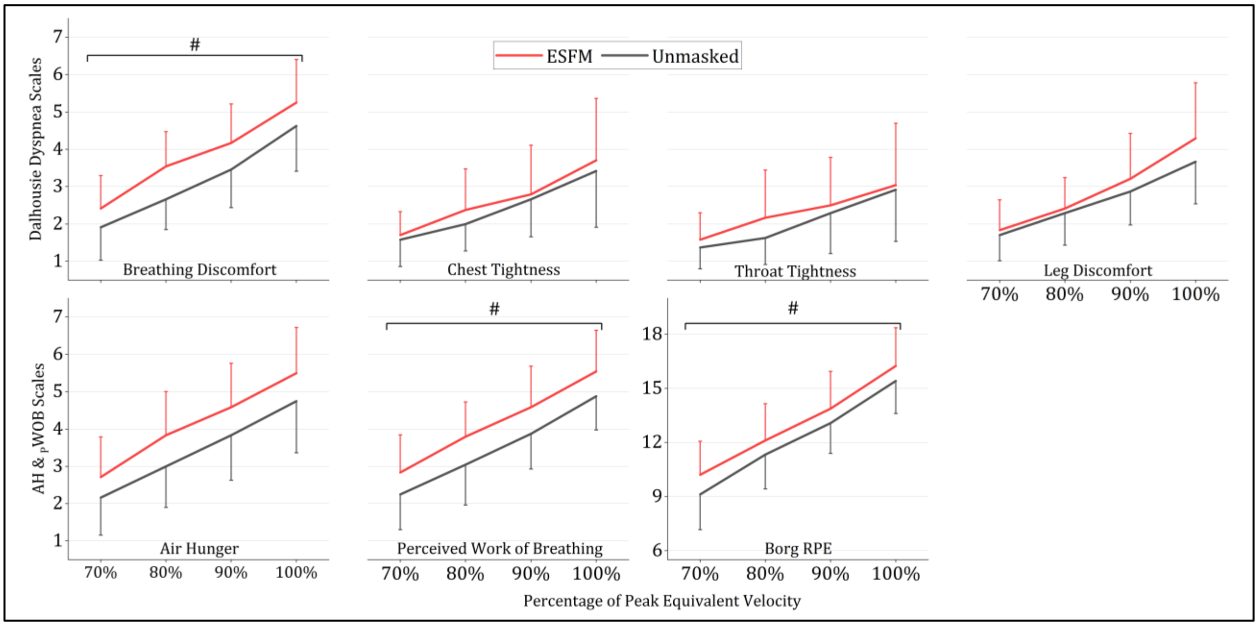

Figure 3. Mean (SD) perceptual responses to treadmill running with (red) and without (gray) an ESFM. # Significant (p<0.05) main effect (condition).

Maximal Physiological and Perceptual Responses

Due to technical issues with data collection equipment, complete SpO_2 data was not captured for five participants at termination under both conditions (n=19). Additionally, *f* data could not be obtained for two participants due to a poorly fitting Equivital monitoring vest (n=22).

Maximal HR at exercise termination was not significantly different between ESFM (184.9 BPM) and control conditions (185.7 BPM, $t(23)=0.669$, p=0.510) with no outliers being identified. The mean *f* at exercise termination was not significantly different between ESFM (61.1 breaths/min) and control conditions (63.1 breaths/min, $t(21)=0.991$, p=0.333). When 2 outlying cases were removed from analysis, differences remained non-significant (ESFM=59.4 breaths/min, control=61.6 breaths/min, $t(19)=1.740$, p=0.098). A significantly lower SpO_2 was observed at termination in the ESFM condition (89.7%) when compared to the control condition (93.4%, $t(18)=3.413$, p=0.003). When 3 outlying cases were removed from the pairwise comparison, significant differences remained (M=89.8%, UM=94.1%, $t(15)=7.312$, $p<0.001$).

Non-parametric tests were used to compare responses in perceptual measures assessed via scales at exercise termination. Use of an ESFM was found to significantly elevate both AH and PWOB at termination. 11/24 participants reported higher perceived AH at termination while wearing an ESFM, with only a single participant reporting reduced air hunger in the ESFM condition (p=0.006). PWOB at termination was higher in the ESFM condition for 12/24 participants with only a single participant reporting a reduced PWOB at termination with an ESFM (p=0.003). No significant differences in perceptual responses to maximal exercise with an ESFM were observed for RPE, session RPE, BD, LD, CT, or TT (***Table 3***).

Table 3. Perceptual and physiological responses to maximal intensity exercise with and without an ESFM.

		ESFM		**CONTROL**		**Mean Difference**	
	n	**Mean (SD)**	**Median**	**Mean (SD)**	**Median**	**(ESFM-CON)**	**p**
Air Hunger (1-7)	24	6.5 (0.8)	7.0	6.0 (1.0)	6.0	+0.5	**0.006***
Perceived Work of Breathing (1-7)	24	6.5 (0.7)	7.0	6.0 (0.93)	6.0	+0.5	**0.003***
Breathing Discomfort (1-7)	24	6.2 (1.0)	6.0	6.1 (1.0)	6.0	+0.1	0.527
Chest Tightness (1-7)	24	4.3 (1.6)	4.5	4.4 (1.7)	4.5	-0.1	0.572
Throat Tightness (1-7)	24	3.8 (2.2)	3.0	4.0 (1.7)	4.0	-0.1	0.730
Leg Discomfort (1-7)	24	5.0 (1.5)	5.5	5.1 (1.6)	5.0	0.0	1.000
Borg RPE (6-20)	24	18.8 (1.2)	19.0	18.4 (1.7)	19.0	+0.3	0.393
Session RPE (0-10)	24	6.5 (2.0)	7.0	6.6 (1.7)	7.0	-0.1	0.799
Heart Rate (BPM)	24	184.9 (10.0)	185	185.7 (12.2)	183	-0.8	0.510
Breathing Frequency (breaths/min)	22	61.1 (9.5)	61	63.1 (9.8)	63	-1.9	0.333
SpO_2 (%)	19	89.7 (5.1)	91	93.4 (3.9)	94	-3.7	**0.003***

**Significant differences between ESFM and control conditions.*

Respiratory Responses

Submaximal respiratory responses were compared across conditions for the first 5 stages of the GXT, as this was the point to which near-complete data was available prior to attrition due to test termination (n=22). Overall (n=22), a significant main effect for condition was observed across several spirometry measures including FEV_1 (F=19.20, p<0.001), FVC (F=4.49, p=0.046), FEF_{25-75} (F=9.05, p=0.007), and FEF_{50} (F=20.00, p<0.001), with use of an ESFM improving respiratory function (Figure 4). PEF and FEV_1/FVC were not significantly different between the ESFM and control conditions. No significant interaction effect between intensity and condition was identified for any of the spirometry measures assessed (Figure 4). When individuals identified as EIB+ (n=6) were analyzed separately, significant submaximal differences in FEF_{25-75} (F=8.46, p=0.033) and FEF_{50} (F=10.88, p=0.022) were identified. In individuals who were EIB- (n=16), significant differences were observed in FEV_1 (F=12.634, p=0.003), PEF (F=5.25, p=0.037), and FEF_{50} (F=10.74, p=0.005) (Figure 4).

Given the presence of outliers, non-parametric pairwise comparisons were performed for the respiratory function comparisons (n=23). When respiratory function at termination was assessed, no significant differences were observed in FEV_1, FVC, FEV_1/FVC, PEF, FEF_{25-75}, or FEF_{50} at termination, expressed as a percentage of the pre-exercise baseline. In contrast, when cumulative exposure was controlled for by assessing responses for the last stage completed by an individual under both experimental conditions, significant differences were observed in both mid-expiratory flow measures. For FEF_{25-75}, 17/23 participants exhibited higher mid-expiratory flow in the masked condition when compared to the unmasked control (P=0.010). Similarly, 16/23 participants exhibited a higher FEF_{50} in the masked condition when expressed as a percentage of baseline (p=0.012)

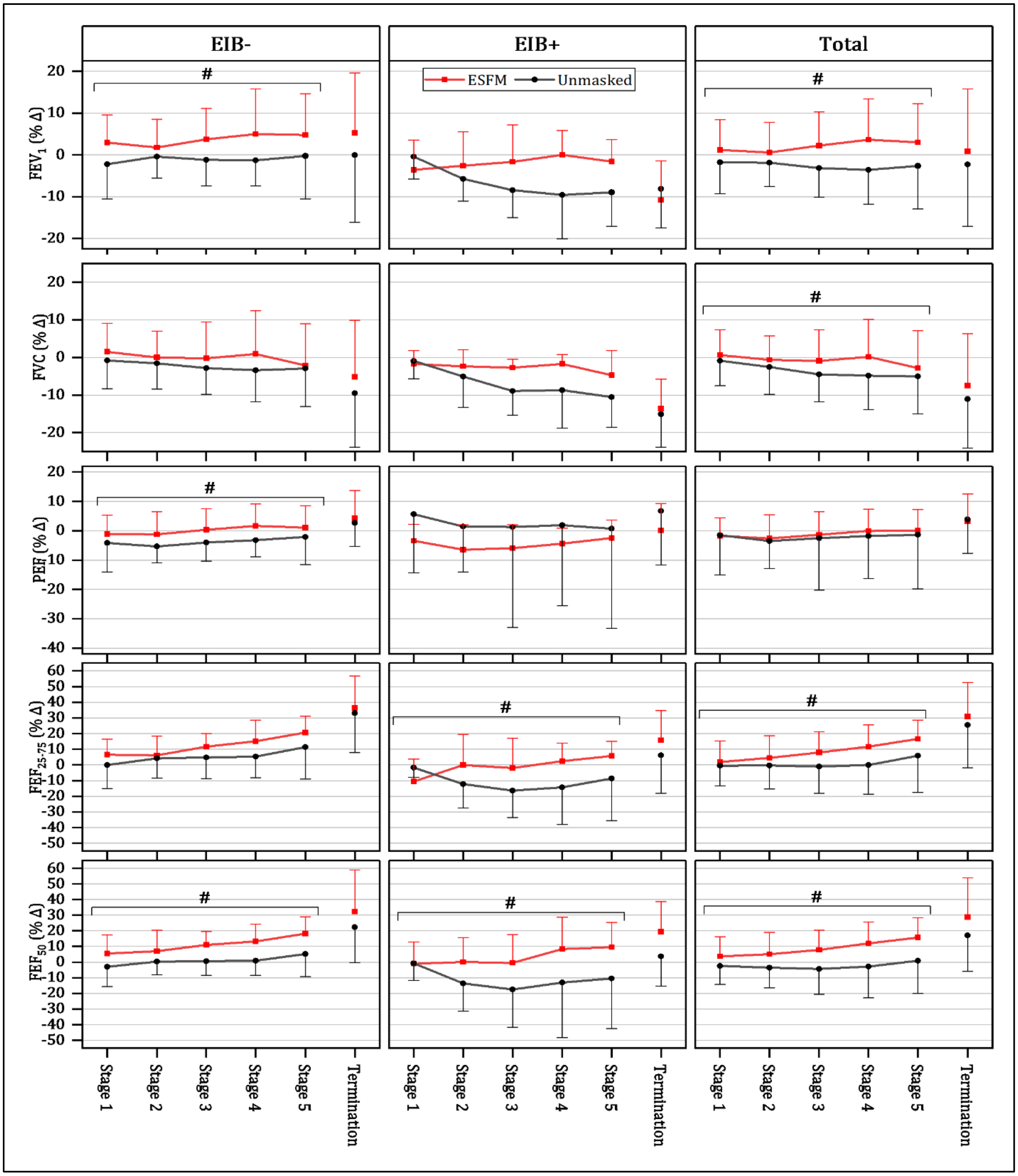

Figure 4. Mean (SD) respiratory responses to submaximal (stages 1-5) and maximal (termination) intensity exercise both with (red) and without an ESFM (gray) as a percentage change from pre-exercise baseline.

Significant main effect of submaximal exercise intensity (stage). No significant interaction effects (Condition x Intensity) were found.

Exercise Performance

Due to the violation of the normality assumption, as determined by a significant Shapiro-Wilk test ($p<0.001$) in combination with the presence of outliers, non-parametric sign tests were used to compare performance across each of the experimental conditions.

21/24 participants had a longer time to exhaustion in the unmasked condition with 3 performing better in the ESFM condition. The median decrease in test performance as assessed through time to exhaustion was statistically significant (-150.5 s) with a shorter median time to exhaustion observed when a mask was worn (2163.0 s) versus when no mask was worn (2216.5 s), $p<0.001$ (Figure 5).

When performance was assessed via the last stage completed for all 24 participants, 13 completed more stages in the unmasked condition, 2 completed more stages in the masked condition, and 9 completed the same number of whole stages under both conditions. A median single-stage impairment was observed in the ESFM condition when compared to the unmasked condition ($p=0.007$).

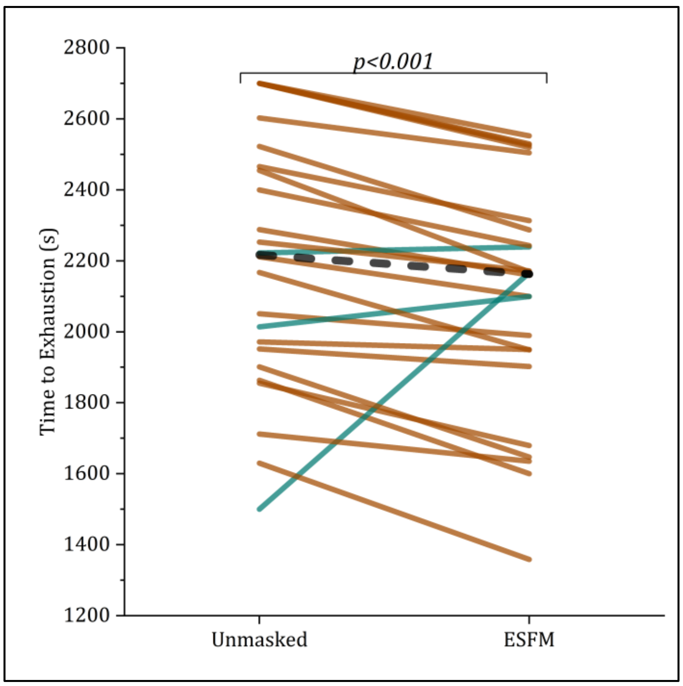

Figure 5. Time to exhaustion (s) during a graded treadmill exercise to volitional exhaustion both with an exercise specific face mask (ESFM) and without (Unmasked). Dashed line represents median differences. Color coded for individuals whose performance improved (blue) or worsened (brown) in the ESFM condition.

3.4 Discussion

As face coverings continue to be worn both for viral protection and to preserve lung function in cold-weather athletes, findings from this study act to inform the use of ESFMs moving forward. Although current evidence has suggested that PFMs likely alter perceptual and cardiopulmonary responses to exercise (5), research on the acute influence of an ESFM on lung function during exercise is non–existent. It has been cited that breakthrough EIB can occur in asthmatics (93), yet the high incidence of EIB in high-ventilation sports necessitates a greater focus on when and how lung function changes during prolonged exercise across a range of intensities. For individuals looking for a simple face covering to be used for the preservation of respiratory function under dry/cold environmental conditions, an ESFM may initially be considered a viable option, with claims of being designed for "easy breathability during high exertion activity" (108). This research addresses this fundamental point by first illustrating an ESFM can help to promote bronchodilation, and this occurs in both EIB+ and EIB- individuals. None the less, this study has also illustrated that even a mask designed for exercise can impose a degree of perceptual and physiological burden, elevating multiple sensations of dyspnea and inducing significant reductions in SpO_2 at both submaximal and maximal exercise intensities. This is an important consideration for high-ventilation athletes, where the impaired performance resulting from altered perceptual and physiological responses may undercut the respiratory protective benefits.

Physiological Impact

Our results reflect an altered physiological response in the masked condition, with a small but consistent increase in HR at higher intensities in the absence of significant changes in *f*. These findings are supported by Zheng and colleagues' meta-analysis (5), where collectively PFM use did not significantly modify *f* during either steady-state (-0.3 breaths/min) or maximal exercise (-1.4 breaths/min). Additionally, although the difference observed in submaximal HR was non-significant, the consistent mean elevation across all submaximal intensities with an ESFM (+2.4 BPM) was similar to that reported in a meta-analysis by Zheng et al. (5) for steady-state exercise with a PFM (+2.7 BPM). The lack of differences in *f* would suggest that any resistance imposed by the ESFM was not substantial enough to depress *f* or significantly modify breathing pattern, with a reduction in peak *f* previously being reported in endurance-trained individuals breathing through a high-resistance metabolic system (~2.5 cmH_2O at 90L/min) when compared to a low resistance alternative (~0.8 cmH_2O at 90L/min) (123). Previous work relying on a singular case study of a 28-year-old recreational male runner ($\dot{V}O_2$ max = 45.6 ml/kg/min) observed a depressed peak *f* with a co-contaminant reduction in peak $\dot{V}_E$ during exercise (24). When the highest-performing participants who completed our protocol in the unmasked condition (n=4) were isolated, mean *f* at termination was not significantly different between conditions (ESFM=62.0 breaths/min, Control =61.1 breaths/min) suggesting that individuals reaching the highest exercise intensity (and therefore likely experiencing some of the highest absolute ventilatory demands) did not experience a modification in breathing dynamics elicited by the mask. It is possible that differences between our work and that of Prado et al. (24) may be in part attributable to differences in experimental intervention, with the combination of a surgical mask and metabolic collection mask likely invoking a greater amount of respiratory resistance when compared to an ESFM alone. With that said, elevations in breathing resistance imposed by the ESFM may have contributed to the non-significant mean elevation in HR we observed across all submaximal exercise intensities, an outcome potentially attributable to increased work of breathing (WOB), which has been shown to positively correlate with increases in respiratory muscle blood flow and cardiac output (124).

The exacerbated reductions in SpO_2 when an ESFM was worn may stem either from a rightward shift in the oxyhemoglobin disassociation curve (OHDC), a reduction in the arterial partial pressure of oxygen (PaO_2), or a combination of the two (125). It is well documented that arterial desaturation is often observed in fit individuals at near-maximal and maximal exercise intensities (126), an occurrence likely attributable to a widening alveolar-arterial O_2 difference, relative hypoventilation, and/or an accentuated rightward shift of the OHDC (125). As the use of a PFM increases both VD and breathing resistance, differences in SpO_2 between conditions may stem from several different underlying sources. Elevated dead space ventilation can modify inspired gas tensions, in turn elevating inspired CO_2 and depressing inspired O_2, although the extent of this change in the context of small dead space volumes of ~100ml is likely minimal (127). Despite this, if hyperpnea is not adequate to compensate for this small difference in inspired gas tensions, either due to blunted chemosensitivity or due to a mechanical ventilatory limitation, resulting reductions in PaO_2 when combined with an accentuated rightward shift of the OHDC may be large enough to induce reductions in SpO_2 (128). Existing literature supports the notion of PFM-induced hypoventilation, with multiple studies demonstrating elevated end-tidal carbon dioxide ($_{ET}CO_2$) when a PFM was worn during both maximal and submaximal exercise (5). Furthermore, given the high prevalence of expiratory flow limitation in trained individuals (87), any resistance imposed by an ESFM is likely to shrink the maximal flow-volume envelope (81, 83). This smaller envelope increases the likelihood of a mechanical limitation to breathing during exercise, which may impair exercise tolerance, particularly with maximal intensity exercise.

The 3.7% mean reduction in SpO_2 at exercise termination likely has pragmatic implications for aerobically fit individuals as once SpO_2 falls by ~3% from rest, any further reductions in SpO_2 have the potential to reduce $\dot{V}O_2$ max by 1-2% per 1% fall in SpO_2, which may be a contributing factor to the significant performance impairment observed with ESFM use (125). Despite this, no significant correlation was found between differences in SpO_2 and differences in performance at termination between conditions (R^2=0.035). Provided that several studies have reported no significant differences in SpO_2 during maximal intensity exercise with a PFM (83, 95), characteristics of our exercise protocol and sample population may have contributed to significant differences. First, larger reductions in SpO_2 are often observed with treadmill running when compared to cycle ergometry, with the difference being potentially attributable to a greater ventilatory response associated with cycling (125). Additionally, although commonly associated with disease, individuals with high aerobic fitness also exhibit a high prevalence of exercise-induced arterial hypoxemia, which is often characterized as a fall in SpO_2 under 93% and may partially explain the greater degree of desaturation observed in our sample (125). Given the high prevalence of mechanical flow limitation in athletes, a reduced maximal flow-volume envelope due to mask resistance may hasten this occurrence resulting in a greater degree of desaturation. Indeed, previous research has demonstrated a link between mechanical flow limitation, dynamic hyperinflation, and reduction in P_aO_2 during exercise (128). Regardless of the underlying mechanism at play, these reductions in SpO_2 were common among our participants, with 89.5% of participants with SpO_2 data at termination exhibiting more desaturation at termination when an ESFM was worn.

Perceptual Impact

Most studies investigating the physiological and perceptual impacts of exercise with a PFM have limited their perceptual measures to RPE and dyspnea (5). Additionally, the use of a metabolic collection mask in combination with a PFM may limit the external validity of perceptual measures used to understand the responses to PFM use (42, 45, 84). Furthermore, although previous studies have reported elevated dyspnea when a PFM was worn during exercise, both alongside (127) and in the absence of (129) significant physiological differences, the specific qualities of dyspnea associated with their use remain unclear. We observed significant elevations in several perceptual measures and no change in others when an ESFM was worn, both at submaximal and maximal exercise intensities. These results are discussed in further detail and are specific to aerobically fit individuals.

It is important to recognize that not all maximal perceptual responses occurred at the same treadmill velocity, attributable to differences in exercise performance between the ESFM and unmasked conditions. With that said, AH and $_P$WOB were the only two perceptual measures that were significantly elevated at termination when an ESFM was worn and these max responses were likely due to the elevated submaximal increases (AH= +0.7, $_P$WOB= +0.7) that remained at maximum (AH= +0.5, $_P$WOB= +0.5) in the ESFM condition (Figure 2). These two measures are distinct contributors to dyspnea yet likely differ in their physiological sources (120). Sensations of air hunger are closely tied to the "balance between respiratory drive arising from chemoreceptors and other inputs versus respiratory tidal excursions reported by mechanoreceptors" (130). Experimentally, air hunger can be induced through both arterial hypoxemia and hypercapnia, with an observable relationship between elevated $_{ET}CO_2$, reduced end-tidal oxygen, and sensations of AH (79). Provided that elevated $_{ET}CO_2$ has been consistently reported during exercise when a PFM is worn (5), PFM-induced changes in blood gas tensions may be partially responsible for elevations in AH observed during submaximal and maximal intensity exercise. Additionally, the greater degree of hypoxemia may have also contributed to elevations in this sensation particularly at higher exercise intensities, with the precipitous drop in SpO_2 being observed during the GXT in the ESFM condition (Figure 2). On the other hand, although $_{P}$WOB during exercise is closely associated with increases in $\dot{V}_E$ under typical circumstances (120), resistance imposed by the ESFM may further elevate this domain of dyspnea during exercise through the elevation of WOB for a given exercise intensity. Indeed, prior research has demonstrated elevated dyspnea with a resistance training mask for a given work rate during exercise (131). In the context of ESFM use, elevated resistance was likely the primary contributor to the observed differences in $_{P}$WOB, given its direct influence on elevating WOB. Taken in concert, our data and the findings of others would suggest that elevations in perceptual effort are partially attributable to added VD and imposed resistance associated with ESFM use, which may dissuade individuals from their use during exercise.

Given the increase in breathing resistance and dead space imposed by a mask is relatively small and likely equivalent to that of a standard cardiopulmonary exercise testing arrangement (16), the degree of perceptual burden observed across submaximal and maximal exercise intensities may be perceived as disproportionate to the imposed physiological burden. When WOB was experimentally modified by increasing resistance during submaximal exercise in healthy participants, no elevations in dyspnea were observed despite imposing breathing resistances several times that of a PFM (132). Similarly, the addition of 600ml of dead space was found to induce additional ventilation but did not elevate dyspnea for an equivalent level of ventilation (133). With this evidence, it is likely that factors in addition to those influencing respiratory function including imposed VD and resistance, contributed to the observed elevations in $_{P}$WOB and AH. It is also possible that factors related to the temperature/humidity of the microenvironment under the mask, the combined inspiratory/expiratory resistance, and the methodological challenges associated with sufficiently blinding participants may have contributed to the perceptual burden associated with PFM use (16), although the specific pathway for this occurrence has not been elucidated.

The Dalhousie Dyspnea Scales and Borg RPE Scale provided further insight into perceptual sensations associated with the ESFM. Both BD and RPE were significantly elevated across submaximal intensities but not at exercise termination. Provided that test performance was significantly impaired when an ESFM was worn, with 54% of participants terminating at a slower velocity in the ESFM condition, it could be hypothesized that termination occurred sooner but at an equivalent level of global perceptual discomfort when an ESFM was worn. This line of reasoning would align with the psychobiological model of endurance performance, where exercise is ceased when the perception of effort and discomfort exceeds one's motivation to continue (134). Given that CT and TT are specific qualities of dyspnea often associated with bronchoconstriction and reductions in airway caliber (135), the lack of significant differences in CT or TT may suggest that the degree of respiratory protection was not sufficient to reduce sensations of CT or TT, although it is possible that other factors associated with PFM use may have confounded these observations. Despite our best efforts to depict these respiratory sensations to participants, it is possible unfamiliarity with these symptoms led TT and CT to be confounded by elevated dyspnea in other domains such as BD, AH, or $_P$WOB (136). Finally, no significant differences were observed in LD during either submaximal or maximal intensity exercise. One potential explanation for this lack of differences could be related to resistance imposed by the ESFM, whereby it was not substantial enough to cause sympathetically mediated vasoconstriction via the respiratory muscle metaboreflex, which has previously been demonstrated to elevate quadriceps fatigue (137).

Respiratory Impact

Although spirometry measures at baseline between the masked and unmasked trials were not significantly different, significant differences were observed during exercise. The use of FVC maneuvers is one of the most common methods used to assess changes in airway caliber associated with exercise and is a valid reflection of airway obstruction (138). The respiratory measures taken during the exercise protocol suggest that the use of an ESFM may help to maintain baseline respiratory function in hyperresponsive individuals and promote bronchodilation in individuals without EIB. Both FEF_{25-75} and FEF_{50} were significantly elevated at 100% peak equivalent velocity when an ESFM was worn. Given these measures of mid-expiratory flow are commonly used as indices of small airway obstruction (139) and these analyses were conducted with matched cumulative exercise exposure, elevations in these variables when an ESFM was worn suggests that use of an ESFM limited the extent to which small airways were brought into the conditioning process. Provided that the ability to adequately condition air in the proximal airways is challenged in dry environmental conditions when $\dot{V}_E$ is increased (51), use of a face mask may act to promote increases in airway caliber, particularly in the small airways, secondary to a reduction in osmotic stress.

Although it is often cited that bronchodilation prevails during exercise even in hyperresponsive individuals such as asthmatics (138), our spirometry data suggests that in those with EIB, bronchoconstriction may occur during prolonged exercise in hyperresponsive individuals. Airway caliber is primarily regulated through tonic parasympathetic cholinergic innervation, which is withdrawn during exercise, leading to increased bronchodilation (140). In our subjects who were classified as EIB+ (n=6), mean FEV_1, FEF_{25-75}, and FEF_{50} fell by roughly 10% in the first 25 minutes of the exercise protocol in the unmasked control condition (Figure 4). Under the ESFM condition, however, EIB+ participants maintained near-baseline respiratory function over this same duration. Although limited research has examined the respiratory-protective benefits of simple face coverings, one study found that respiratory function reductions were significantly attenuated when a surgical mask was worn in asthmatic children, with marked post-exercise improvements in FEV_1 and FEF_{50} (109). Furthermore, there is literature documenting the efficacy of heat & moisture exchange masks that can attenuate reductions in respiratory function during exercise in cold/dry environments (11, 14). Thus, it is likely that an ESFM acts via a similar mechanism to limit the osmotic stress that leads to bronchoconstriction, with our results illustrating that this can be protective under seemingly benign indoor conditions.

Although the benefits of wearing a face covering during exercise have been largely promoted to those with EIB (47), there may also be acute benefits for those without EIB. In this cohort (n=16), FEV_1, PEF, and FEF_{50} were significantly elevated when a mask was worn, suggesting use of an ESFM promotes additional bronchodilation when worn during exercise. There is evidence to suggest increasing the absolute water content of inspired air can also promote bronchodilation in healthy individuals without asthma (141). Although the specific mechanism for this occurrence was not hypothesized, the ESFM may act via a similar mechanism in EIB- individuals, by delaying or preventing the small airways from being used to condition relatively dry inspired air. Research examining the responses of healthy athletes exercising in cold, dry environmental conditions has also demonstrated the ability of a heat & moisture exchange device to improve post-exercise respiratory function (142). While these findings are suggestive of an acute benefit in non-responsive individuals, chronic benefits of reducing the burden of conditioning may also exist, with animal studies in canines suggesting repeated dry air hyperpnea can lead to airway remodeling (143). This is also suggested by research on competitive winter sport athletes, where significantly higher levels of inflammatory exudate in the airway were observed, with authors recommending limiting osmotic and thermal stress often experienced as part of training (144). By limiting the extent to which peripheral airways are required to condition inspired air, the use of an ESFM could have a respiratory protective benefit, acutely promoting increased airway caliber and potentially limiting airway hyperresponsiveness. This likely results in improved long-term lung health, where long-term remodeling might occur not just in cold-weather athletes (144) but also in individuals who habitually exercise in dry climates.

Performance Impact

As previously discussed, performance was significantly impaired in the masked condition, as assessed by both time to exhaustion and the last stage completed (Figure 5). Provided that 88% of participants performed worse when an ESFM was worn as indicated by time to exhaustion, it is worth considering why this may be the case. Considering that RPE and BD were not significantly different between experimental conditions at termination, it could be speculated that voluntary exercise termination occurred at the point at which discomfort exceeded individual motivation to continue. As the ESFM elevated RPE and BD across submaximal exercise intensities, the threshold at which exercise was no longer perceptually tolerable likely occurred sooner in the GXT under these conditions. Although there are competing schools of thought as to whether exercise performance is predominantly consciously or subconsciously regulated, perception of effort is undoubtedly integral to one's willingness to continue exercise (65). Provided vigorous encouragement was provided by research staff for all exercise trials and the fact that participants were highly motivated, it is unlikely the observed differences in performance were due to submaximal participant effort.

Although collective research findings suggest a lack of performance impairment when cloth or surgical masks are worn (5), the utilization of a longer GXT protocol consisting of 5-minute stages likely amplified the performance impairment in this study. Additionally, given our sample consisted of aerobically fit individuals including many endurance athletes, even small reductions in the maximal flow volume envelope induced through mask resistance have the potential to expedite a ventilatory limitation, provided that endurance athletes are more likely to be flow limited at peak exercise when compared to healthy individuals (23). Our findings of elevated AH and $_{P}$WOB with maximal intensity exercise with an ESFM are suggestive of a potential flow limitation at peak exercise causing premature exercise termination. This has been shown by others (145) where resistance-induced expiratory flow limitation is linked to elevated perceived difficulty in breathing and impaired performance in healthy adults. Regardless of the mechanism underpinning impaired performance, our participants illustrate that willingness to wear an ESFM, particularly in athletic competitions is likely low. Specifically, the results of our study suggest that performance in prolonged, high-intensity aerobic exercise events would be impaired in aerobically fit individuals when an ESFM is worn.

Limitations

Given the nature of the intervention, it was not possible to blind participants to the experimental condition. A 'placebo mask' which contains a hole in the center has been used previously (83) however this likely was not effective at preventing participants from being aware of what condition they were in. Additionally, the use of spirometry for within-exercise assessment of respiratory function may potentially be confounded by poor effort or respiratory muscle fatigue (116). However, provided that the face mask may elicit a greater degree of respiratory muscle fatigue, the degree of protective effect would merely be underestimated if this were the case. It could also be argued that the exercise provocation of this study may have been insufficient to induce bronchoconstriction in all participants with EIB, leading some to be misclassified as EIB-. As guidelines for EIB exercise provocation recommend that high ventilation be rapidly achieved and maintained for 6-8 minutes, it is possible that the lower intensity exercise in the first stages of the GXT may have increased too slowly for immediate recruitment of smaller airways to take place (49). Given the first stages likely elicited a relatively low $\dot{V}_E$ particularly in more aerobically fit participants, it is possible that some participants were misclassified as EIB-. Despite this, the prolonged nature of this protocol may have been necessary to elicit within-exercise changes in respiratory function, which has been previously reported in EIB+ cross-country skiers (15).

Although we intended to assess both maximal and submaximal responses with a single protocol, use of the same GXT protocol for all participants meant that our analyses were restricted by the results of our lowest-performing participant. As such, the lowest exercise intensity that data was available for all participants (n=24) was 70% peak equivalent velocity. Based on pooled HR data from the unmasked condition, this intensity equated to roughly 78% maximum HR, which is classified by the ACSM as vigorous intensity (25). However, provided the training history of our participants, ACSM's guidelines for exercise intensity may not be the most appropriate intensity prescription for athletes, with 78% HR max equating to a sub-threshold intensity when a model for athletes was used (146). Although ideally stage velocities would have been matched to each participant's fitness level, limitations in resources and the unavailability of metabolic testing due to the COVID-19 pandemic prevented this from occurring. It is possible that exercise intensities below 70% peak equivalent velocity would have elicited different physiological and perceptual responses, however, given that these velocities elicited an effort that was 'Very Light' for participants as indicated by mean RPE ratings, our approach to the analysis is likely a valid representation of intensities aerobically fit individuals would choose to exercise at if they were to go and complete a treadmill workout or other like forms of aerobic exercise.

3.5 Conclusion

Based on these results, the use of an ESFM during exercise is appropriate in healthy and aerobically fit individuals. We found elevated perceptual burden with some physiological changes, although the specific link between perceptual and physiological changes is not entirely clear. Despite the heightened perceptual discomfort when wearing an ESFM during exercise, improved within-exercise respiratory function indicates that ESFMs can benefit respiratory function in both individuals with and without EIB. This finding suggests that use of an ESFM during exercise may elicit a respiratory-protective benefit. Despite this benefit, the reduction in time to exhaustion observed would suggest limited utility in endurance sport competition, where maximal aerobic performance is paramount. Given that ESFMs act as a 'double-edged sword' when worn during exercise, imposing a perceptual burden- and reducing performance while promoting respiratory function, future research should focus on the development and evaluation of face coverings that impose minimal perceptual and physiological burden during exercise while still providing respiratory-protective benefits to the user.

Chapter 4: General Discussion

Methodological Merits & Shortcomings

Provided that data collection for this study took place amid the COVID-19 pandemic, we were required to adapt certain aspects of our exercise protocol. Although the study was originally intended to be performed outdoors, logistical challenges with this arrangement necessitated the use of a controlled laboratory environment, which is conducive to studies where the same ambient conditions are required. Although this adaptation allowed for much more control over the testing environment and therefore improved internal validity, as certain aspects of the protocol were optimized for an outdoor setting, some measures that could have been captured indoors were not. With the originally proposed protocol, metabolic testing was not included, and the exercise protocol was designed to be universal, with a wide range of intensities that could be performed by a spectrum of aerobically fit individuals. The inclusion of metabolic testing would have allowed us to better characterize the aerobic fitness of our sample and would have also allowed us to normalize physiological and perceptual responses as a percentage of $\dot{V}O_2$ max, which would have given our analysis more granularity. Furthermore, maximal metabolic testing would have also allowed us to tailor the graded exercise protocol to each participant's fitness level, better controlling for total exposure which would have simplified analyses of respiratory responses.

Upon reflection, I believe the methodology used achieved the overall purpose and provides some novel data in several paradigmatic areas. The exclusive use of non-obstructive measurements allowed participants to give a truly maximal effort without being hampered by instrumentation, preserving the external validity and generalizability of our findings. As such, these findings can readily be applied in practice, which is a core tenant of sports science (147). Within the context of research investigating PFM use during exercise, this study also is positioned on a methodological continuum that has its strengths and weaknesses. On one side of the spectrum, you have studies that decided to collect a large number of physiological measures, often through the use of indirect calorimetry (42, 45, 84). Although this approach has allowed for an improved understanding of PFM-induced changes in aerobic metabolism, gas exchange, and ventilation, the obtrusive nature of this approach has the potential to alter the perceptual and performance responses (148). On the other hand, other studies took a contrasting approach, focusing solely on perceptual measures that could be collected non-obtrusively (105). Although these studies provide an excellent degree of insight into real-world responses, they do not provide substantial insight into the underlying physiology, which is often necessary to adequately contextualize the observed perceptual responses. In the middle of this continuum, there are numerous studies that clearly understood the confounding effect of metabolic data collection while understanding the importance of assessing physiological measures. These studies, of which I would include this study, utilized novel data collection methods and techniques to capture some physiological measures without sacrificing outcomes related to perceptual responses or exercise performance. These novel approaches included the use of a modified mouthpiece (17) or nasal cannula (149) that allowed for a mask to be worn traditionally while still assessing end-tidal gases or integrating PFM material into a disposable droplet filter (43). Likewise, the use of a wireless physiological monitoring vest in our study allowed for the assessment of respiratory rate and HR in a way that did not interfere with respiratory function or perceptual measures. Although not without their limitations, these study designs allowed for valid physiological & perceptual responses to be assessed and provide real-world data on how a PFM influences exercise responses during aerobic exercise.

Participant Recruitment and the COVID-19 Pandemic

As outlined in our research methods, we aimed to recruit a sex-balanced sample of aerobically fit individuals. Given we were unable to collect metabolic data, selection of participants based on $\dot{V}O_2$ max could not be performed, and thus we relied on self-reported training status and history to inform which participants were included. This resulted in our sample being less homogenous than anticipated and acutely influenced our ability to normalize responses to lower submaximal exercise intensities. A more homogenous cohort with a higher mean level of aerobic fitness and associated GXT performance would have allowed for lower submaximal intensities to be investigated. Although it may have been possible to do this via an additional exercise protocol designed to indicate one's level of aerobic fitness, adding an additional day of testing would have likely made participant recruitment more difficult. Despite the ever-present difficulties associated with participant recruitment in exercise research, we were able to exceed our target sample size which allowed for adequate power to identify differences in our key outcomes.

One positive aspect of our investigation was the ability to recruit a roughly balanced sample of both males and females. Given the historical exclusion/omission of female participants in exercise physiology research (150), contemporary research should be conducted with a sex-balanced sample. Although this study was not intended to, nor adequately powered to examine sex differences, the inclusion of both male and female participants allowed for improved external validity and generalizability of findings. With that said, there are most definitely steps that could have been taken to ensure a better characterization of our sample and allow for better interpretation of our data in relation to sex. Specifically with regards to our female participants, although all participants self-identified as female, inquiring about reproductive maturation, phase of menstrual cycle, and contraception status has been strongly recommended when including female participants in exercise physiology research (150). In future studies, this would be a consideration to control for physiological changes linked to hormonal fluctuation over the menstrual cycle, which has been shown to modestly reduce exercise performance during the late follicular phase (151) and alter RPE during exercise (152).

Assessment Methodology for Perceptual Responses

Given the pertinence of perceptual responses to ESFM use, we chose to assess a range of perceptual responses relating to both breathing discomfort and physical exertion. The combined use of the Dalhousie Dyspnea Scales and the assessment of $_P$WOB and AH allowed for a thorough indication of perceptual discomfort and effort across a range of exercise intensities. Specifically, the use of the Dalhousie Dyspnea Scales, a set of pictorial scales which have previously been validated for assessment of dyspnea related to exercise (153), gave us insight into both general breathing discomfort and respiratory sensations of CT and TT, which are often associated with bronchoconstriction (119). Although it was hypothesized that these sensations of dyspnea would be reduced as a result of attenuated bronchoconstriction when an ESFM was worn, no significant differences in these variables were observed. Given the inherently complex set of psychological, physiological, and neurological factors that interact to influence one's perception of effort and dyspnea, confounding variables and sensations may have contributed to a lack of differences in this domain. It is possible that individuals who were unfamiliar with this sensation misinterpreted general respiratory discomfort as CT. Provided that CT is a respiratory symptom closely tied to bronchoconstriction (135), it is likely certain participants had not experienced this sensation previously and therefore perceptually confounded the different respiratory sensations, despite our best efforts to characterize them. Furthermore, TT has also been associated with EILO and it is therefore possible that this rapidly resolving airway obstruction was not identified through spirometry and confounded perceptual changes related to airway caliber.

Although often overlooked, perceptual responses to exercise are an invaluable indicator and in the context of ESFM use, are likely influential in informing one's decision to wear a face covering. Despite the clear respiratory-protective benefit of wearing a face covering while exercising in a dry environment, it is important to consider these benefits alongside perceptual responses, which indicate an elevated level of discomfort associated with mask use during both submaximal and maximal intensity exercise. Even if there is a clear benefit to wearing an ESFM from a respiratory health perspective, many individuals will likely be unwilling to tolerate the elevated perceptual burden. In this context, the so-called 'holy grail' would be an ESFM design that elicits an inconsequential degree of resistance combined with minimally added VD, while retaining the ability to aid in the conditioning of inspired air. This would allow for a near-normal level of ventilation to be comfortably maintained, which would likely eliminate the significant reduction in arterial oxygen saturation observed with increasing exercise intensity. Given the positive and negative aspects of the ESFM are somewhat co-dependent however, this type of design may not be possible. Some masks that are currently on the market may come close however, with heat & moisture exchange masks developed by Airtrim (Airtrim Sport, Vapro AB, Västerås, Sweden) imposing 0.1L of dead space and <0.5 cmH_2O of resistance with high-intensity exercise hyperpnea ($\dot{V}_E$= 180L/min) (154). Furthermore, although research has demonstrated their efficacy in attenuating EIB in cold-air environments (155), these masks may still have a deleterious impact on cold-air exercise performance and may elevate the physiological demands of submaximal and maximal-intensity exercise (156). In conjunction with our findings, it is evident that further technical development of high-performance face coverings is needed.

Widespread Implications

All considered, despite a reduction in widespread public masking as the transition is made from the COVID-19 pandemic, the findings of this study have important implications in several key contexts. Most importantly, given the significant respiratory protective benefit observed in individuals with EIB, this study adds to the existing body of literature suggesting that even a simple face covering is sufficient to adequately aid in the conditioning of inspired air and subsequently reduce bronchoconstriction. Second, given that limited research has been conducted on the respiratory responses to prolonged exercise in dry environments, spirometry measures from this study demonstrated that within-exercise reductions in respiratory function associated with dry air hyperpnea can be attenuated through use of an ESFM, with benefits also being observed in individuals without EIB. Provided that both airway remodeling and the development of airway hyperresponsiveness are of concern for high-ventilation athletes who often train and compete in cold/dry environments (144), these types of relatively inexpensive face coverings may be a viable option for the preservation of both acute and chronic respiratory health. This recommendation is likely most applicable to prolonged aerobic exercise where exercise performance is not paramount, and the elevated perceptual burden is tolerable. Finally, despite these benefits, there are evident drawbacks to use of an ESFM in aerobically fit individuals undertaking maximal intensity exercise, with an elevated perceptual burden occurring alongside reductions in SpO_2 and exercise performance. To conclude, further research is needed, both in the development of face coverings that do not elicit a significant perceptual and physiological burden as well as into feasible methods that reduce the degree of osmotic stress and associated respiratory consequences in those who chronically exercise in cold/dry environments.

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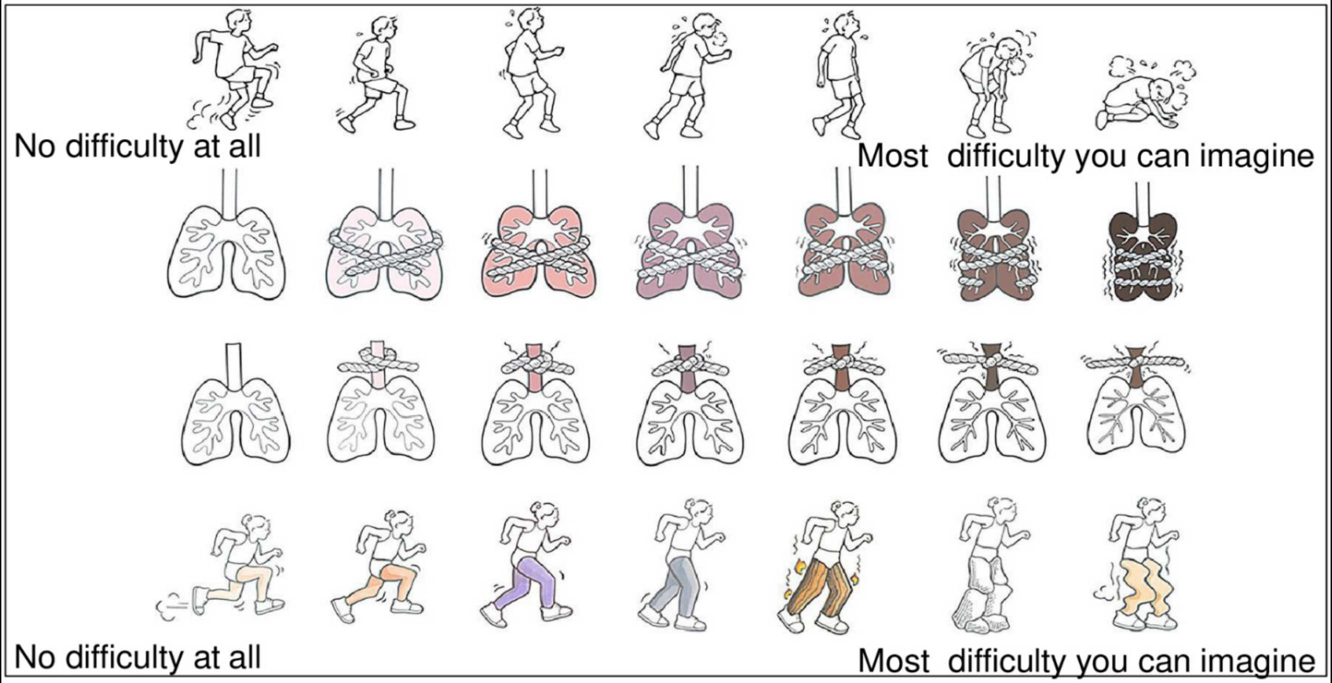
Appendices

Appendix A

Dalhousie Dyspnea Scale (119).

Dalhousie Dyspnea and Perceived Exertion Scale



- **For the top set of pictures tell us how does your breathing feel (how hard).**
- **For the second set of pictures tell us how tight your chest feels.**
- **For the third set of pictures tell us how tight your throat feels.**
- **For the final set of pictures tell how do your legs feel.**

Appendix B

Air Hunger and Perceived Work of Breathing Scale (81).

Sense Of Air Hunger And Sense Of Work And Effort Of Breathing

*Please rate your "**air hunger**" defined as sense of air hunger as the discomfort caused by your urge to breathe, a feeling of being starved for air.*

*Please rate your "**work or effort to breath**" defined as the sensations associated with the amount of work or effort to satisfy your breathing requirements.*

- **"None"** - felt none of the requested sensation.
- **"None plus"**
- **"Slight" -** sure that I felt the sensation but the feeling is not very strong or unpleasant and I could tolerate it for a very long time.
- **"Slight plus"**
- **"Moderately strong" -** felt a strong level of the requested sensation, but could continue at this level for several minutes.
- **"Moderately strong plus"**
- **"Extreme" -** The requested respiratory sensation has reached a maximum level. (In the case of air hunger, this would be intolerable.)

Modified from: Lansing, Robert W., et al. "The perception of respiratory work and effort can be independent of the perception of air hunger." American Journal of Respiratory and Critical Care Medicine 162.5 (2000): 1690-1696.