03/07/2021
MSc Human and Applied Physiology
King's College London

Research Project in Human & Applied Physiology

Module: 7BBLM009

Student's Name: Ilya Bychkov

Email Address: [redacted]

Title of Project: Understanding the work of breathing associated with ejection seat angle and clothing

Supervisor's name: Ross Pollock

Number of Words: 9654

I have read the College Regulations on Cheating and Plagiarism and state that this piece of work is my own and does not contain any unacknowledged work from any other hand-written, printed or Internet source. I further state that I have acknowledged all sources used and quoted in the attached work. I understand the penalties that can be applied in cases of proven cheating and plagiarism.

A. I have performed all the experiments described in this project. YES
   If no, please list the procedures described in the project that were performed by others;
B. I confirm that I have submitted an electronic copy to www.submit.ac.uk that is identical to the written copies of this project.

Signature [redacted]   Date: 30/08/2021

Understanding the work of breathing associated with ejection seat angle and clothing

Module: 7BBLM009

Student's Name: Ilya Bychkov

Supervisor's name: Dr Ross Pollock

A report submitted in partial fulfilment of the requirements for the degree of MSc Human & Applied Physiology at the King's College London.

August, 2021

Understanding the work of breathing associated with ejection seat angle and clothing

Key Point Summary

Abstract

Modern military aircraft are often designed to operate at the physiological limits of their pilots. This has previously led to several physiological problems reported by pilots of the newest Gen 4 and 5 aircraft, including F-22 Raptor and F-35 Lightning II. The causes of these episodes have still not been identified and are likely to involve an interaction of breathing gas issues and increased work of breathing. However, there is little to no data showing the effects of the ejection seat configuration, jacket weight and harness on the work of breathing of the pilots. In this study, several physiological variables including parasternal EMG, PTPdi, end-tidal gases, and dynamic compliance were measured in different combinations of ejection seat back angles (at 20, 35, and 50-degrees), jacket (jacket on with weighted pockets and life preserver unit and jacket off) as well as having the harness on or off. The key findings of the study were that the jacket on conditions lead to increased work of breathing at 35 and 50 degrees (PTPdi increased by up to 83.8 cmH2O.s/min and EMGpara%max increased by up to 4.33% with the jacket on). The jacket also increased the end-tidal CO2 by 1.1mmHg at 35 degrees. The changes seen in the study likely occurred due to the increased resistance to breathing caused by the pressure applied by the weight of the jacket onto the chest. Further investigation is necessary to understand the physiological mechanisms of the changes observed and to quantify the changes caused by the presence of G-forces and different breathing mixtures to further our understanding of the changes in work of breathing seen in pilots of high-performance aircraft.

Abbreviations

AUC, Area Under The Curve; BRAG, Breathing Regulator Anti-G; BTPS, Body Temperature And Pressure Saturated; ECG, Electrocardiogram; EMG, Electromyography; EMGpara%max, Parasternal Electromyography As A Percentage Of Maximum Voluntary Contraction; FIVC, Forced Inspiratory Vital Capacity; FRC, Functional Residual Capacity; HRCAS, House Of Representatives Committee Of Armed Services; LPU, Life Preserver Unit; MBA, Martin Baker Aircraft Company; MEP, Maximum Expiratory Pressure; MIP, Maximum Inspiratory Pressure; MVC, Maximum Voluntary Contraction; NASA, National Aeronautical And Space Administration; NEDU, Navy Experimental Diving Unit; NRD, Neural Respiratory Drive; OBOGS, On-Board Oxygen Generation System; PE, Physiological Episode; PIRD, Powered Inertia Restraint Device; PTPdi, Pressure-Time Product Of The Diaphragm; rmsEMG, Root Square Mean Of Electromyography; RR, Respiratory Rate; SAB, Scientific Advice Board; SNIP, Sniff Nasal Inspiratory Pressure; SpO2, Oxygen Saturation; USAF, United States Air Force; VO2resp, Respiratory Muscle Oxygen Consumption; WoB, Work Of Breathing;

MeSH Keywords: Work of Breathing, Military Aircraft, Ejection Seat

Introduction

Physiological Episodes

Every new fighter aircraft model is designed to be more manoeuvrable, to fly faster and higher than the previous model. This has led to a peculiar situation where the pilots' physiology became the limiting factor of the aircraft performance. In 2011, US Air Force stood down the entire fleet of the 165 F-22 jet fighters for four months due to pilots reporting disorientation, difficulty breathing, and problems with vision (BBC, 2012). These incidents are attributed to occurrences of physiological episodes (PE). However, the specific cause of the PE occurrences has still not been identified. However, there are several theories that can be used to explain these episodes, including hypoxia, breathing gas impurities, and increased work of breathing.

During the investigations, the USAF concentrated on the effects of hypoxia and breathing mixture contamination. However, the findings of these investigations were inconclusive, likely suggesting the episodes have been caused by a complex interaction of different causes.

One of the potential causes mentioned in the investigations by the USAF Scientific Advisory Board was the presence of contaminants, such as carbon monoxide and volatile organic compounds, in the breathing mixture of the pilots. However, the placement of a filter to remove the contaminants had little to no effect on the physiological episode incidence. (USAF Scientific Advisory Board, 2012)

The report presented to the House of Representatives Committee of Armed Services (HRCAS) suggested that the leading cause of the PE occurrences to be "*the supply of oxygen delivered to the pilots, not the quality of oxygen delivered to the pilots*". (Bartlett *et al.*, 2012)

The oxygen to the pilots' masks is delivered by a system known as an on-board oxygen generation system (OBOGS). The OBOGS in the F-22 aircraft has two settings: AUTO and

MAX. When the OBOGS is set to MAX, it delivers up to 94% oxygen into the pilots' masks, compared to between 45% and 65% when OBOGS is set to AUTO. During normal USAF and Army operations, the AUTO setting was used up to a cabin altitude of 11000ft. Above 11000ft and during Navy operations, the OBOGS was usually set to MAX. Following the reports of the physiological episodes and finding that hypoxia was a likely cause, the pilots were advised to use the MAX setting during normal operation below 11000ft cabin altitude. However, the switch to OBOGS MAX had an opposite effect on the incidence of PEs, with incidence doubling following the new instructions. This suggested that the OBOGS settings were unlikely to be the leading cause of the physiological episodes reported by the F-22 pilots.

However, the work of breathing associated with the OBOGS has also been identified as a potential cause of the development of PE. The potential role of the work of breathing in PE was identified following work conducted by the US Navy Experimental Diving Unit (NEDU) and NASA. NEDU and NASA found in 2012 that the OBOGS increased the work of breathing, thus limiting the quantity of oxygen delivered to the pilots, especially during +Gz force exposures and performance of physically demanding tasks. The increase in work of breathing was likely caused by the filters, hoses, and the breathing regulator and anti-G (BRAG) valve. (Cragg *et al.*, 2020)

Due to the likelihood that the work of breathing contributed significantly to the development of physiological episodes in F-22 pilots, it is vital that the effects of the different seat and clothing configurations on the work of breathing are understood. The improved understanding of these effects will allow the designers of the future aircraft platforms to limit or prevent any adverse effect of platform design on the work of breathing and hopefully prevent the repeat of the physiological issues seen in the F-22 fleet.

Ergonomics of Ejection Seats

In addition to the prevention of physiological episodes, Martin-Baker Aircraft Company (MBA) have expressed interest in the understanding of the effect of seat back angle in order to optimise the comfort of the pilot. During MBA's own internal research, it was identified that if the seat back angle were increased beyond 30 degrees, the pilot would be able to sit in the seat for prolonged periods of time. This was attributed to the pressure from the pilot's weight being redistributed around the seat, from the seat bucket to the seat back. The increase in pilot comfort has recently become a significant focus in aircraft and seat design. This has become a significant focus of companies with the ever-increasing lengths of sorties (flights of military aircraft), with the average sortie length reaching 5 hours and the maximum sortie length being limited by the pilots (due to the mid-flight refuelling capabilities of the modern fighters). (Wiegand *et al.*, 2018)

The limitation of the sortie length by the pilot made it vital that the comfort of the pilot can be maximised. However, before the seat back angle to be used in future platforms can be decided, it is essential that the effect of the increased seat back angle on the pilot's physiology is understood in order to minimise any adverse interactions.

Aims and Hypothesis

The study has four main aims. The first aim is the investigation of the effects of wearing a flight jacket with a life preserver unit (LPU) as well as weighted pockets to simulate the weight worn by flight crews during normal operations on the work of breathing. The second aim is to investigate the effect of wearing an ejection seat harness on the work of breathing. The third aim is the investigation of the effect of the seat back angle on the work of breathing. The final aim is the investigation of the interaction of different combinations of clothing, harness states, and seat back angles on the work of breathing.

We hypothesise that the work of breathing will increase with an increase of seat back angle and weight on the chest exerted by the jacket and harness being on.

Materials and Methods

Subject Information

11 non-smoking subjects between 18 and 45 years old were recruited for the study from students and staff at King's College London and Martin-Baker Aircraft Company (MBA). However, only 8 subjects were able to participate in the study, with 3 subjects not meeting the inclusion/exclusion criteria or withdrawing from the study. The anthropometric measurements of the subjects are presented in Table 1. All subjects gave informed consent, and the study was approved by King's College London Ethics Committee. Prior to participation, all subjects have tested negative for COVID-19 using rapid lateral flow tests on the day of participation.

Table 1 Anthropometric data of the 8 subjects who were able to participate in the study, broken down by sex.

Sex	Measure	Mean	SD	N (%)
Male	Age	23	0	3 (37.5)
	Height (cm)	180.2	10.3	
	Weight (kg)	78.9	17.6	
Female	Age	24.8	3.56	5 (62.5)
	Height	166.7	4.39	
	Weight	62.2	9.52	

Exclusion Criteria

Subjects who are smokers, have respiratory conditions, or have breathing problems/difficulties were excluded from the study due to the potential of these conditions to worsen as a result of participation or affect the results obtained by the study. Furthermore, due to the need for the use of a nasal catheter for the measurement of transdiaphragmatic pressure, those with recent mid-facial or upper gastro-intestinal trauma or surgery, as well as those with abnormal oesophageal anatomy, were excluded from the study due to complications these can cause with the passage of the catheter.

Experimental Protocol

The testing was carried out in the King's College Hospital Chest Unit. The subjects attended a single 2-hour session.

Jackets

The subjects were fitted with a flight jacket (either small or large size). The total weight of the small jacket with weighted pockets and life preserver unit (LPU) was 7.771 kg (small jacket with LPU: 2.245kg, pocket 1: 2.772kg, pocket 2: 2.754kg). The total weight of the large jacket with weighted pockets and LPU was 7.681kg (large jacket with LPU: 2.155kg, pocket 1: 2.772kg, pocket 2: 2.754kg).

Seat and Harness

The seat used for testing was an MBA Mk-16E ejection seat. The Mk-16E seat is the same ejection seat model currently installed on the F-35 Lightning II aircraft. The seat height was adjusted as per MBA instructions to ensure the subject is seated at the correct height. During testing, the seat back angle was adjusted using an actuator to 3 different angles: 20°, 35°, or 50°. The angles were measured using a protractor with a weight, as shown in Figure 9 in Appendix A: Photos.

For the harness on conditions, the seat's 5-point harness was fitted to the subjects according to the MBA instructions. The harness was exerting a 7lbs (3.17kg) across both shoulder straps through the powered inertia restraint device (PIRD). During testing, it was ensured that the PIRD straps were parallel to the ground, indicating that the harness was set up correctly.

Condition Combinations

All subjects were exposed to all 12 conditions. The order of conditions was randomised for each subject. The subjects were exposed to each condition, presented in Table 2, for 3 minutes with the data recorded as described in the Data Recording section. An example of the jacket and harness on at 20° is presented in Appendix A: Photos in Figure 10.

Table 2 The combination of the 12 conditions used for the study. Each of the 8 subjects was exposed to each of these conditions for 3 minutes.

Jacket	Harness	Angle
Off	Off	20
		35
		50
	On	20
		35
		50
On	Off	20
		35
		50
	On	20
		35
		50

Data Recording

The data were recorded continuously throughout the subject's exposures to the conditions, except the oxygen saturation (SpO2). However, for the purposes of the analysis, the last 1 minute of the data recordings were used to allow the subject to adjust to each condition over the first 2 minutes.

Measurement of Cardiovascular Effects

The subject's oxygen saturations were measured at the end of each condition using a pulse oximeter (ChoiceMMed, Beijing, China). Furthermore, throughout the experiment, the subject's electrocardiogram (ECG) was recorded. The lead II ECG was recorded using ECG electrodes (Covidien Kendall), ECG leads and an ADInstruments BioAmp (Oxford, UK). The ECG was then recorded in the LabChart (channel 1 in Figure 11) and used to calculate the subject's heart rate (channel 18 in Figure 11).

Measurement of Respiratory Effects

Spirometry and Gas Analysis

Prior to testing, the ADInstruments pneumotachograph was calibrated using a 3-litre syringe. The ADInstruments gas analyser was also calibrated using a 16% O2/5% CO2 gas mix.

During testing, the subjects were fitted with a face mask (Hans Rudolph, Shawnee, KS, USA). The face mask was connected to the ADInstruments spirometry pod (connected to the ADInstruments pneumotachograph) and the ADInstruments gas analyser. The pneumotachograph was used to record the flow in LabChart v8 (channel 2 in Figure 11), which was used to calculate the volume, tidal volume, respiratory rate, and minute ventilation (channels 10, 11, 12, 13 in Figure 11, respectively).

Parasternal EMG

For parasternal EMG recording, the subjects were connected to a 1902 pre-amplifier (CED, Cambridge, UK) (gain: 1000x, low pass filter: 2000Hz, high pass filter: 10Hz, sampling frequency: 2000Hz). The positive and negative electrodes were placed on prepared chest skin in the 2nd intercostal space, either side of the sternum, as described by Reilly et al. The reference electrode was placed on the shoulder of the subject. (Reilly *et al.*, 2011) The EMG was recorded using PowerLab 16/35 (ADInstruments, Oxford, UK) in LabChart v8 software (channel 9 in Figure 11). The EMG channel was then used to calculate the root square mean of the EMG (channel 19 in Figure 11).

Transdiaphragmatic Pressure

The transdiaphragmatic pressure (channel 8 in Figure 11) was calculated using the gastric and oesophageal pressures recorded using a dual pressure transducer tipped catheter (Gaeltec, Dunvegan, UK). The gastric and oesophageal pressure transducers were calibrated using the CN553 pressure meter and known pressures.

The subject's nose and throat were anaesthetised using Xylocaine 10mg spray in order to suppress the gag reflex during catheter insertion. The catheter was then inserted into the stomach and oesophagus via a nostril. The placement of the catheter was confirmed by performing several SNIP manoeuvres, with the catheter adjusted to ensure correct placement.

Methods

Once the subjects were fitted with a flight jacket and had the seat height adjusted, the subjects had been connected to the ECG and EMG, as well as had the oesophageal/gastric catheter inserted.

The subjects performed maximal breathing manoeuvres, consisting of 3x SNIP, 3x MIP, and 3x MEP manoeuvres, while EMG, ECG, gastric, oesophageal, and mouth pressure were recorded.

Mouth pressure was recorded using a custom occlusion device with a leak valve connected to MKIS (GM Instruments, Irvine, UK). Following maximal breathing manoeuvres, the subjects were fitted with a face mask, and their forced inspiratory vital capacity (FIVC) was measured.

Following the recording of the SNIPs, MIPs, MEPs and FIVC, the subjects were exposed to the conditions described in Table 2 for 3 minutes in a randomised order. During the exposures, the subject's ECG, O2, CO2, oesophageal and gastric pressures, and parasternal EMG were recorded continuously, as described previously in the paper. After each 3-minute exposure, the subject's SpO2 was measured, followed by a measurement of FIVC.

Data Extraction

Parasternal EMG

The parasternal EMG data was extracted, as described previously by MacBean et al., by calculating the root mean square of the EMG (rmsEMG) using 5ms intervals (MacBean *et al.*, 2016). The EMG data was then recorded for 5 breaths per condition that were not "contaminated" with the ECG signal or movement artefacts. The mean rmsEMG was then recorded for each of the 5 breaths. The rmsEMG data was then converted to a percentage of a maximum EMG obtained from either SNIP, MIP, MEP, or FIVC performed prior to testing. The mean values of the 5 breaths were calculated to be used in the data analysis. The mean rmsEMG and respiratory rate for each condition were then used to calculate the neural respiratory drive.

Transdiaphragmatic Pressure and Respiratory Duty

The transdiaphragmatic pressure data were recorded from 5 breaths, not contaminated with swallowing or cardiac interference, taken in the last minute of each condition. An example of data obtained for the transdiaphragmatic pressure is shown in Figure 12 (Appendix B: Traces and Data Pads). The area under the curve (AUC) of the transdiaphragmatic and oesophageal pressure channels was calculated for each breath. The pressure-time product of the diaphragm (PTPdi) was then calculated using:

$$PTPdi = Pdi\ AUC * \frac{60}{Breath\ Time}$$

The respiratory duty cycle was calculated by dividing the inspiratory time by the total breath time. The PTPdi and respiratory duty were recorded for each of the 5 breaths per condition. The mean of the 5 breaths was then used for data analysis.

Dynamic Compliance

The dynamic compliance was measured for the same 5 breaths per condition as for the PTPdi. The volume of the breath and the change in the oesophageal pressure was used to calculate the dynamic compliance by using:

$$Dynamic\ Compliance = \frac{Breath\ Volume}{Poes\ Change}$$

The data for each condition is the mean of the dynamic compliance for the 5 breaths.

Other Measurements

The respiratory rate, end-tidal O_2 and CO_2, heart rate, tidal volume, and minute ventilation were extracted by calculating the mean values over the last 30 seconds of each condition exposure. The tidal volume and minute ventilation were corrected for the body temperature and pressure saturated (BTPS) conditions.

Statistical Analysis

The data were analysed using GraphPad Prism 9 software which was used for statistical analysis and plotting the graphs. The statistical analysis was performed using three-way repeated-measures

ANOVA with Tukey post-hoc test. The difference was considered significant if the p-value was less than 0.05. The data are presented as mean (SD) unless stated otherwise.

Results

Cardiovascular Responses

Heart Rate

The heart rate data is presented in Figure 1(A) in Result Figures. The heart rate for the last 30 seconds of each exposure did not show any significant changes between the different conditions (three-way repeated-measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, the mean (SD) heart rates were 74 bpm (10 bpm), 71 bpm (10 bpm), 71 bpm (11 bpm) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the heart rates were 74 bpm (11 bpm), 71 bpm (11 bpm), 68 bpm (11 bpm) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage, the heart rates were 73 bpm (11 bpm), 70 bpm (11 bpm), 68 (11 bpm) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage, the heart rates were 72 bpm (11 bpm), 72 bpm (10 bpm), 68 bpm (10 bpm) at 20, 35, and 50 degrees, respectively.

Oxygen Saturations

The SpO_2 data is presented in Figure 1(B) in Result Figures. The SpO_2 for each exposure did not show any significant changes between the different conditions (three-way repeated measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, SpO_2 were 98.6% (0.52%), 98.1% (0.69%), 98.0%, (0.76%) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the SpO_2 were 98.5% (0.53%), 98.4% (1.20%), 98.4% (0.52%) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the SpO_2 were 98.4% (0.92%), 98.6% (0.74%), 98.0% (1.07%) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the SpO_2 were 98.6% (0.79%), 98.6% (0.74%), 98.1% (0.90%) at 20, 35, and 50 degrees, respectively.

Respiratory Responses

Tidal Volume

The tidal volume data is presented in Figure 2(A) in Result Figures. The tidal volume for each exposure did not show any significant changes between the different conditions (three-way repeated measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, tidal volumes were 0.84 L (0.39L), 0.89L (0.45L), 0.86L (0.31L) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the tidal volumes were 0.90L (0.43L), 0.84L (0.31L), 0.87L (0.42L) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage, the tidal volumes were 1.01L (0.57L), 0.83L (0.47L), 0.82L (0.42L) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage, the tidal volumes were 0.81L (0.44L), 0.81L (0.32L), 0.86L (0.50L) at 20, 35, and 50 degrees, respectively.

Respiratory Rate

The respiratory rate (RR) data is presented in Figure 2(B) in Result Figures. The RR for each exposure did not show any significant changes between the different conditions (three-way repeated-measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, RR were 16.4 BPM (3.3 BPM), 15.6 BPM (3.9 BPM), 14.6 BPM (4.2 BPM) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the RR was 14.9 BPM (3.6 BPM), 15.3 BPM (3.7 BPM), 15.9 BPM (3.2 BPM) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage, the RR was 14.4 BPM (4.5 BPM), 16.5 BPM (4.0 BPM), 15.9 BPM (3.3 BPM) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage, the RR was 15.8 BPM (4.9 BPM), 17.1 BPM (3.5 BPM), 16.3 BPM (5.6 BPM) at 20, 35, and 50 degrees, respectively.

Minute Ventilation

The minute ventilation (V_M) data is presented in Figure 2(C) in Result Figures. The V_M for each exposure did not show any significant changes between the different conditions (three-way repeated-measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, V_M was 13.2 L/min (4.9 L/min), 12.8 L/min (4.2 L/min), 12.0 L/min (3.9 L/min) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the V_M was 12.7 L/min (4.6 L/min), 12.2 L/min (3.8 L/min), 12.8 L/min (3.9 L/min) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage, the V_M was 12.3 L/min (4.1 L/min), 12.2 L/min (4.2 L/min), 12.0 L/min (4.1 L/min) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage, the V_M was 11.7 L/min (4.1 L/min), 13.3 L/min (4.2 L/min), 12.6 L/min (4.4 L/min) at 20, 35, and 50 degrees, respectively.

End Tidal

End-tidal O2

The EtO2 data is presented in Figure 3 (A) in Result Figures. The EtO2 for each exposure did not show any significant changes between the different conditions (three-way repeated-measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, EtO2 were 111.0 mmHg (6.95 mmHg), 112.0 mmHg (8.09 mmHg), 109.8 mmHg (6.05 mmHg) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the EtO2 were 111.6 mmHg (7.71 mmHg), 110.1 mmHg (7.25 mmHg), 110.9 mmHg (6.02 mmHg) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the EtO2 were 111.2 mmHg (9.37 mmHg), 110.3 mmHg (5.47 mmHg), 110.0 mmHg (6.63 mmHg) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the EtO2 were 111.9 mmHg (6.30 mmHg), 111.8 (6.95 mmHg), 111.1 mmHg (6.63 mmHg) at 20, 35, and 50 degrees, respectively.

End-tidal CO2

The EtCO2 data is presented in Figure 3 (B) in Result Figures. During the harness off/jacket off stage, EtCO2 were 38.6 mmHg (2.36 mmHg), 39.1 mmHg (2.28 mmHg), 40.1 mmHg (2.10 mmHg) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the EtCO2 were 39.3 mmHg (2.56 mmHg), 40.1 mmHg (1.87 mmHg), 40.0 mmHg (1.92 mmHg) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the EtCO2 were 39.3 mmHg (3.26 mmHg), 39.6 mmHg (2.29 mmHg), 39.9 mmHg (2.38 mmHg) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the EtCO2 were 38.9 mmHg (2.01 mmHg), 39.3 (2.29 mmHg), 39.9 mmHg (2.38 mmHg) at 20, 35, and 50 degrees, respectively.

The EtCO2 had increased significantly at 35 degrees with no jacket when the harness was put on (three-way repeated-measures ANOVA, $p=0.0299$, $n=8$). There was an increase of 1.06 mmHg when the harness was put on compared to when the harness was on. There were no other significant changes between the different conditions (three-way repeated-measures ANOVA $p>0.05$, $n=8$)

Work of Breathing

rmsEMG

The rmsEMG data is presented in Figure 4 in Result Figures. During the harness off/jacket off stage, rmsEMG were 5.11%MVC (2.01%MVC), 4.00%MVC (1.21%MVC), 4.82%MVC, (1.97%MVC) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the rmsEMG were 5.57%MVC (3.59%MVC), 5.16%MVC (2.59%MVC), 4.14%MVC (1.40%MVC) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage, the rmsEMG were 4.20%MVC (2.36%MVC), 6.92%MVC (3.01%MVC), 8.20%MVC (5.49%MVC) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage, the rmsEMG were 6.95%MVC

(5.04%MVC), 5.56%MVC (4.02%MVC), 8.73%MVC (2.89%MVC) at 20, 35, and 50 degrees, respectively.

The rmsEMG increased significantly at 50 degrees with the harness on when the jacket was put on (three-way repeated-measures ANOVA, $p=0.0495$, $n=8$). There was an increase of 4.33% when the jacket was put on. Furthermore, there was a significant increase in rmsEMG when the harness and jacket were put on at 50 degrees seat back angle (three-way repeated-measures ANOVA, $p=0.0305$, $n=8$). This increase was 3.91%.

Neural Respiratory Drive

The neural respiratory drive (NRD) data is presented in Figure 5 in Result Figures. The NRD for each exposure did not show any significant changes between the different conditions (three-way repeated measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, NRD was 84.3 %.BPM (31.2 %.BPM), 66.5 %.BPM (23.2 %.BPM), 70.7 %.BPM (26.0 %.BPM) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the NRD was 85.2 %.BPM (59.0 %.BPM), 74.9 %.BPM (28.2 %.BPM), 67.7 %.BPM (25.3 %.BPM) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the NRD was 58.4 %.BPM (26.1 %.BPM), 116.7 %.BPM (67.6 %.BPM), 129.5 %.BPM (90.9 %.BPM) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the NRD was 102.4 %.BPM (53.1 %.BPM), 89.6 %.BPM (56.5 %.BPM), 148.0 %.BPM (80.5 %.BPM) at 20, 35, and 50 degrees, respectively.

Pressure time product of the diaphragm

The pressure-time product of the diaphragm (PTPdi) data is presented in Figure 6 in Result Figures. During the harness off/jacket off stage, PTPdi was 145.6 cmH2O.s/min (52.3 cmH2O.s/min), 131.1 cmH2O.s/min (59.9 cmH2O.s/min), 146.0 cmH2O.s/min (46.8 cmH2O.s/min) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the PTPdi was 142.5 cmH2O.s/min

(60.8 cmH2O.s/min), 158.9 cmH2O.s/min (88.4 cmH2O.s/min), 176.2 cmH2O.s/min (40.9 cmH2O.s/min) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the PTPdi was 205.6 cmH2O.s/min (61.4 cmH2O.s/min), 169.5 cmH2O.s/min (71.5 cmH2O.s/min), 176.9 cmH2O.s/min (50.1 cmH2O.s/min) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the PTPdi was 144.9 cmH2O.s/min (61.3 cmH2O.s/min), 196.9 cmH2O.s/min (66.9 cmH2O.s/min), 229.8 cmH2O.s/min (64.1 cmH2O.s/min) at 20, 35, and 50 degrees, respectively.

There was a significant decrease in the PTPdi at 20 degrees with the jacket on when the harness was put on (three-way repeated-measures ANOVA, p=0.0340, n=8). There was a decrease of 60.7 cmH2O.s/min when the harness was put on. Furthermore, there was a significant increase in PTPdi at 35 and 50 degrees when the jacket and harness were put on (three-way repeated-measures ANOVA, p=0.00536 (for 35 degrees) p=0.0243 (for 50 degrees), n=8). There was a decrease of 65.8 cmH2O.s/min and 83.8 cmH2O.s/min at 35 and 50 degrees, respectively.

Respiratory Duty

The respiratory duty data is presented in Figure 7 in Result Figures. The respiratory duty for each exposure did not show any significant changes between the different conditions (three-way repeated-measures ANOVA, p>0.05, n=8). During the harness off/jacket off stage, respiratory duty was 0.474 (0.114), 0.456 (0.098), 0.444 (0.095) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the respiratory duty was 0.427 (0.083), 0.445 (0.101), 0.437 (0.097) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the respiratory duty was 0.455 (0.134), 0.467 (0.105), 0.440 (0.088) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the respiratory duty was 0.430 (0.065), 0.450 (0.083), 0.429 (0.065) at 20, 35, and 50 degrees, respectively.

Dynamic Compliance

The dynamic compliance data is presented in Figure 8 in Result Figures. The dynamic compliance for each exposure did not show any significant changes between the different conditions (three-way repeated measures ANOVA, $p>0.05$, $n=8$). During the harness off/jacket off stage, dynamic compliance was 108.5 ml/cmH2O (53.8 ml/cmH2O), 104.2 ml/cmH2O (51.7 ml/cmH2O), 97.3 ml/cmH2O (61.5 ml/cmH2O) at 20, 35, and 50 degrees, respectively. During the harness on/jacket off stage, the dynamic compliance was 110.9 ml/cmH2O (57.3 ml/cmH2O), 106.0 ml/cmH2O (60.8 ml/cmH2O), 86.8 ml/cmH2O (51.1 ml/cmH2O) at 20, 35, and 50 degrees, respectively. During the harness off/jacket on stage the dynamic compliance was 102.6 ml/cmH2O (48.1 ml/cmH2O), 112.7 ml/cmH2O (65.1 ml/cmH2O), 90.4 ml/cmH2O (60.1 ml/cmH2O) at 20, 35, and 50 degrees, respectively. During the harness on/jacket on stage the dynamic compliance was 96.7 ml/cmH2O (56.7 ml/cmH2O), 97.4 ml/cmH2O (51.0 ml/cmH2O), 89.2 ml/cmH2O (48.4 ml/cmH2O) at 20, 35, and 50 degrees, respectively.

Discussion and Conclusions

We have found that there were significant changes in the end-tidal CO2, %rmsEMG(max), and pressure time product of the diaphragm in different conditions. There were no changes in dynamic compliance, neural respiratory drive, or "basic" respiratory variables.

EtCO2

The increase in EtCO2 seen at 35 degrees with the harness on when the jacket was put on or taken off suggested that the weight of the jacket interfered with the respiratory system's ability to meet the metabolic demands of the body for removal of CO2. This likely occurred due to the participants' minute ventilation not increasing in line with the metabolic demands of the body. This is supported by the finding that the respiratory rate and minute ventilation of the subjects in this study did not change significantly at any conditions. This would suggest that if there was an increase in the metabolic demands, the ventilation and thus the ability of the respiratory system to remove CO2 would be compromised.

Furthermore, the increase in the EtCO2 can be caused by a decrease in cardiac output. However, due to this study not measuring the metabolic data and cardiac output, it is hard to identify the specific cause of the changes in the end-tidal CO2 measurements. (Weil *et al.*, 1985; Monnet *et al.*, 2013). This means that there is a need for further investigation into the potential physiological causes of the increase in the end-tidal CO2. This would require a further investigation of the metabolic changes and the cardiac output to determine whether the increase in EtCO2 seen in this study was caused by respiratory, cardiovascular, metabolic, or any combination of these changes.

Further to the changes seen in the EtCO2 with the increased weight on the chest caused by the flight jacket, the flight jackets effect on the functional residual capacity (FRC). This is because the changes in the functional residual capacity have been previously identified as a potential cause of changes in EtCO2. In 2004, Gisolf et al. found that the tidal volume, cardiac output, and FRC were involved in the determination of the end-tidal CO2. (Gisolf *et al.*, 2004). We have found that none of the condition combinations tested in this study had any significant effects on the tidal volume or heart rate. It is, therefore, likely that the effects of the jacket on the EtCO2 are caused by the changes in the FRC or the stroke volume.

Another potential mechanism of the jacket affecting the EtCO2 is because of the jacket weight on the heart stroke volume. The weight of the jacket on the chest may be transferred onto the heart and the great vessels. This could restrict the cardiac preload due to the reduced ability of the blood to return to the heart or due to an increased afterload due to the pressure created by the jacket's weight. This could lead to a decrease in cardiac output via restriction of the stroke volume. If this restriction of the stroke volume is significant, it would explain the increase in EtCO2 due to the finding of this study that there were no significant effects of the different conditions on the heart rate. Therefore, if the stroke volume is reduced by the presence of the jacket, it is likely that the cardiac output with the jacket is reduced, compromising the ability of the subject to move the carbon dioxide from the muscle and other organs to the lungs to be removed. (Shibutani *et al.*, 1994)

Irrespective of the physiological reasons for the increased EtCO2, the increase in the EtCO2 is suggestive of an increase in blood CO2 concentration or hypercapnia. The symptoms of hypercapnia include dizziness, headaches, fatigue, and inability to concentrate. These symptoms are caused by the vasodilation of the cerebral blood vessels and increased cerebral blood flow. (Ito *et al.*, 2003; Law *et al.*, 2017). The symptoms of hypercapnia are very similar to the symptoms reported by the F 22 pilots experiencing the physiological episodes. (Saghaei *et al.*, 2014; Wiegand *et al.*, 2018). This is of interest as it would suggest that the increased CO2 blood levels could be a potential cause of some of the physiological episodes. However, the role of CO2 in the physiological episodes, though it would be of interest to study, the logistics of reliable and accurate arterial CO2 level testing preclude accurate measurements in the in-flight aircraft situations. However, measurement of EtCO2 in-flight may be of interest as part of further investigations into the cause of physiological episodes.

Suppose the further investigation of the role of blood CO2 levels is suggestive of the involvement of hypercapnia in physiological episodes. It would therefore be likely that the possibility of reducing flight jacket weight would need to be investigated by the aircraft design teams in order to reduce the effect of the jacket on the EtCO2 and, by extension, the blood CO2 levels.

rmsEMG

In this study, we had shown that the parasternal rmsEMG as a percentage of the maximum voluntary contraction (EMGpara%max) increased significantly at 50 degrees with the harness on when the jacket was put on.

The EMGpara%max increase seen during the study suggests that the work of breathing of the subjects had increased at 50 degrees with the harness when the jacket was put on. EMGpara%max has been used by a number of researchers to measure the effort of breathing (Bellani & Pesenti, 2014). Thus, the increase of the EMGpara%max suggests that the effort produced by the subject's parasternal intercoastal muscles had increased significantly when the jacket was put on at 50 degrees. The likely explanation of this result is the effort of the parasternal muscles to allow the expansion of the chest during breathing against the weight of the jacket.

Interestingly, the current study results are only partially in agreement with the results of previously published studies. The results of the increase in seat back angle agree with previous research, which suggested that the change from seated to reclined positions had no significant effect on the EMGpara%max. However, from this previous research, it could be expected that there would still be changes in EMGpara%max caused by the presence or absence of the jacket at other seat back angle. (Williams *et al.*, 2019). However, a likely explanation of the absence of any significant changes in EMGpara%max at other angles is that the force produced by the jacket on the chest was not equal at different seat back angles. The jacket can be described as a body sitting on an inclined plane. Therefore, the force created by the jacket's weight on the chest opposing the breathing effort can be described by the below equation.

$$Chest\ Wall\ Force\ from\ Jacket = (jacket\ mass) * 9.81 * \cos(90 - seat\ back\ angle)$$

According to the above equation, the mean force perpendicular to the seat back exerted by the jackets on the chest at different angles was: 30.9N at 20 degrees, 68.5N at 35 degrees, and 73.1N at 50 degrees. Therefore, at 50 degrees, the jackets produced the greatest force on the chest wall opposing the effort of breathing. This is the likely explanation why there was only a significant change in EMGpara%max at 50 degrees when the jacket was put on.

Pressure-time product of the diaphragm

The pressure-time product of the diaphragm (PTPdi) showed a significant decrease at 20 degrees when the harness was put on with the jacket on. PTPdi also showed a significant increase when the jacket was put on with the harness at 35 and 50 degrees.

Measurement of PTPdi has been used extensively in clinical and research practices to measure the work of breathing (Field *et al.*, 1984; Fauroux *et al.*, 2003). Previously published research has found that the PTPdi correlates strongly with the oxygen consumption of the diaphragm and respiratory muscles (VO2resp) (Brochard *et al.*, 1987; Soust *et al.*, 1989), making it a valuable tool in understanding the work of breathing.

The increase in the PTPdi seen when the harness and jacket were put on at 35, and 50 degrees likely occurred due to the weight of the jacket affecting the work that must be performed by the diaphragm. This would occur due to the weight of the jacket pressing on the chest wall with the forces described in the Discussion and Conclusions rmsEMG section. This pressure from the jacket would lead to increased resistance to the expansion of the chest, leading to an increase in work of breathing.

Furthermore, the increased effort required to expand the chest and lower the diaphragm would be expected to increase the oxygen consumption of the respiratory muscles. This is supported by the finding that the PTPdi, which is correlated to the VO2resp, has increased with the jacket and harness being put on.

However, the decrease in the PTPdi seen at 20 degrees when the harness was put on was not expected. The harness did not produce changes in any other variable, except the PTPdi at 20 degrees seat back. The lack of effect of harness on any other variable is likely due to limited force produced by the harness, through the PIRD, on the chest. When done up properly, the PIRD should limit the total force, through the two straps, on the chest to 3.1kg (7lbs, 31.1N). This is done as not to restrict the movement of the pilot during normal flight. During ejection, the PIRD should pull the pilot into the correct position in the seat prior to ejection, similarly to the pre-tensioner found in cars. However, to identify the cause of the decrease in PTPdi with the harness on, further investigations are required. It is, however, likely that the decrease in the PTPdi was anomalous and could be "avoided" by an increase in sample size to enable anomalous results like this to be identified.

Conclusions

In conclusion, there have been several important changes in the work of breathing and respiratory responses identified by this study. The investigation of the causes of the changes seen in this study could form the basis of further research. It is also likely that for the future designs of aircraft platforms, the weight on the pilots' chest should be minimised, especially if the seat back angle is increased to improve pilot comfort and reduce the cardiovascular effects of G-forces.

Study Limitations

There have been several limitations identified with this study design. The two limitations that likely had the most significant effect on the results of the study were the use of surface parasternal EMG and most subjects being female.

Use of Parasternal EMG

Firstly, there was a paper published recently (after the design of the study has been finished) that suggested that the parasternal EMG has several significant limitations (Tagliabue *et al.*, 2021). The paper by Tagliabue et al. has identified that the parasternal EMG is limited when used for research due to the number of artefacts created by the muscle activity of the neighbouring muscle groups such as the pectoralis muscles. A potential solution to this would be the use of direct fine wire electrodes implanted into the parasternal muscle. However, despite the clear advantages of the fine wire EMG method regarding its accuracy, its usability would be limited in our study. This is due to the physical interference of the jacket on the electrodes. These limitations could be avoided by the use of a catheter-based EMG, such as a multi-pair oesophageal electrode catheter, which would be able to record the EMG of the diaphragm muscles, as described by Ramsook et al. (Ramsook *et al.*, 2017).

Furthermore, during parasternal EMG recording, the subject must be able to relax completely in order to prevent artefacts from other muscle groups. However, several subjects found that they could not relax their shoulder and neck muscles at 50 degrees due to finding the seat set up uncomfortable at that angle. This likely further interfered with the recordings at 50 degrees leading to a likely overestimation of the rmsEMG(max) during the 50-degree exposures. This limitation could be prevented or minimised by utilising a pillow or helmet in order to support the participant's head during the 50-degree exposures. The other limitation of the EMG recording method is that the subject's legs were not on the ground during the 35 and 50-degree exposures. This further caused the subjects to support their legs with muscular activity, leading to a likely overestimation of the rmsEMG values.

Majority Female Subjects

The study had a majority of female participants (62% female). However, even with the current recruitment drives attempting to encourage more female fighter pilots, it is still a majority male-dominated profession, with 98% of USAF fighter pilots being male (Schulker *et al.*, 2018). We, therefore, recognise that the study mainly looking at female participants may not be representative of the fighter pilot population. This can be a limitation due to the known differences in the male and female breathing patterns, especially in the utilisation of abdominal or thoracic breathing. (Ragnarsdóttir & Kristinsdóttir, 2006). The use of majority female subjects could lead to an overestimation of the effect of the jacket due to females utilising thoracic breathing, meaning the weight placed on the chest with the jacket may have a greater effect on females' breathing. Furthermore, there have been differences found in the energy usage by male and female respiratory muscles. (Guenette *et al.*, 2010). This could lead to further overestimation of the effects of seat back angle, harness, and clothing.

References

Bartlett RG, Lobiondo FA, Fleming JC, Rooney T, Platts TR, Hartzler V, Runyan J, Roby M, Jones WB, Akin WT, Wilson J, Turner M, Shuster B & Lamborn D. (2012). Committee of armed services report on F–22 pilot physiological issues.

BBC. (2012). F-22 fighter jets face more Pentagon safety rules. In *BBC*.

Bellani G & Pesenti A. (2014). Assessing effort and work of breathing. *Curr Opin Crit Care* **20,** 352-358.

Brochard L, Pluskwa F & Lemaire F. (1987). Improved efficacy of spontaneous breathing with inspiratory pressure support. *Am Rev Respir Dis* **136,** 411-415.

Cragg C, Richards WL, Hall K, Graf JC, Haas JP, Kennedy KD, Matty CM, Shelton MB, Wellner PJ, Alexander DJ, Schallhorn CS, Dietrich DL, Iverson DL, Hodge MW, Pleil JD, Sobus JR & Less J. (2020). NASA Engineering and Safety Center Technical Assessment Report on Pilot Breathing Assessment. **1**.

Fauroux B, Hart N, Luo YM, MacNeill S, Moxham J, Lofaso F & Polkey MI. (2003). Measurement of diaphragm loading during pressure support ventilation. *Intensive Care Medicine* **29,** 1960-1966.

Field S, Sanci S & Grassino A. (1984). Respiratory muscle oxygen consumption estimated by the diaphragm pressure-time index. *J Appl Physiol Respir Environ Exerc Physiol* **57,** 44-51.

Gisolf J, Wilders R, Immink RV, Van Lieshout JJ & Karemaker JM. (2004). Tidal volume, cardiac output and functional residual capacity determine end-tidal CO2 transient during standing up in humans. *The Journal of Physiology* **554,** 579-590.

Guenette JA, Romer LM, Querido JS, Chua R, Eves ND, Road JD, McKenzie DC & Sheel AW. (2010). Sex differences in exercise-induced diaphragmatic fatigue in endurance-trained athletes. *Journal of Applied Physiology* **109,** 35-46.

Ito H, Kanno I, Ibaraki M, Hatazawa J & Miura S. (2003). Changes in human cerebral blood flow and cerebral blood volume during hypercapnia and hypocapnia measured by positron emission tomography. *J Cereb Blood Flow Metab* **23,** 665-670.

Law J, Young M, Alexander D, Mason SS, Wear ML, Méndez CM, Stanley D, Ryder VM & Van Baalen M. (2017). Carbon Dioxide Physiological Training at NASA. *Aerosp Med Hum Perform* **88,** 897-902.

MacBean V, Hughes C, Nicol G, Reilly CC & Rafferty GF. (2016). Measurement of neural respiratory drive via parasternal intercostal electromyography in healthy adult subjects. *Physiol Meas* **37,** 2050-2063.

Monnet X, Bataille A, Magalhaes E, Barrois J, Le Corre M, Gosset C, Guerin L, Richard C & Teboul JL. (2013). End-tidal carbon dioxide is better than arterial pressure for predicting volume responsiveness by the passive leg raising test. *Intensive Care Med* **39,** 93-100.

Ragnarsdóttir M & Kristinsdóttir EK. (2006). Breathing movements and breathing patterns among healthy men and women 20-69 years of age. Reference values. *Respiration* **73,** 48-54.

Ramsook AH, Mitchell RA, Bell T, Calli S, Kennedy C, Lehmann J, Thompson M, Puyat JH & Guenette JA. (2017). Is parasternal intercostal EMG an accurate surrogate of respiratory neural drive and biomarker of dyspnea during cycle exercise testing? *Respiratory Physiology & Neurobiology* **242,** 40-44.

Reilly CC, Ward K, Jolley CJ, Lunt AC, Steier J, Elston C, Polkey MI, Rafferty GF & Moxham J. (2011). Neural respiratory drive, pulmonary mechanics and breathlessness in patients with cystic fibrosis. *Thorax* **66,** 240-246.

Saghaei M, Matin G & Golparvar M. (2014). Effects of intra-operative end-tidal carbon dioxide levels on the rates of post-operative complications in adults undergoing general anesthesia for percutaneous nephrolithotomy: A clinical trial. *Adv Biomed Res* **3,** 84.

Schulker D, Yeung D, Keller KM, Payne LA, Saum-Manning L, Hall KC & Zavislan S. (2018). Understanding Demographic Differences in undergraduate pilot training attrition.

Shibutani K, Muraoka M, Shirasaki S, Kubal K, Sanchala VT & Gupte P. (1994). Do changes in end-tidal PCO2 quantitatively reflect changes in cardiac output? *Anesth Analg* **79,** 829-833.

Soust M, Walker AM & Berger PJ. (1989). Diaphragm VO2, diaphragm EMG, pressure-time product and calculated ventilation in newborn lambs during hypercapnic hyperpnoea. *Respir Physiol* **76,** 107-117.

Tagliabue G, Ji M, Suneby Jagers JV, Lee W, Dean D, Zuege DJ, Wilde ER & Easton PA. (2021). Limitations of surface EMG estimate of parasternal intercostal to infer neural respiratory drive. *Respiratory Physiology & Neurobiology* **285,** 103572.

USAF Scientific Advisory Board. (2012). Report on Aircraft Oxygen Generation.

Weil MH, Bisera J, Trevino RP & Rackow EC. (1985). Cardiac output and end-tidal carbon dioxide. *Crit Care Med* **13,** 907-909.

Wiegand C, Bullick BA, Catt JA, Hamstra JW, Walker GP & Wurth S. (2018). F-35 Air Vehicle Technology Overview.

Williams S, Porter M, Westbrook J, Rafferty GF & MacBean V. (2019). The influence of posture on parasternal intercostal muscle activity in healthy young adults. *Physiological Measurement* **40,** 01NT03.

Acknowledgements

The author gratefully acknowledges the contributions of Mani Coonjobeeharry and Leann Maanum by way of data collection and extraction. The author would also like to thank Dr Ross Pollock for his guidance as the project supervisor and his contributions to data extraction. The contributions of Martin Baker Aircraft Company are also graciously acknowledged for the provision of the Mk16E ejection seat and their expertise in the operation of the seat as well as the design process of an ejection seat. The contributions of Dr Caroline Jolley's expertise in the measurement of oesophageal and gastric pressures, as well as analysis of the parasternal EMG and pressure data, are graciously recognised. The author would also like to acknowledge Dr James Clark for his contribution to the statistical data analysis and interpretations. Finally, Ms Alexandra Eyles-Owen is thanked for proofreading this manuscript.

Result Figures

A

B

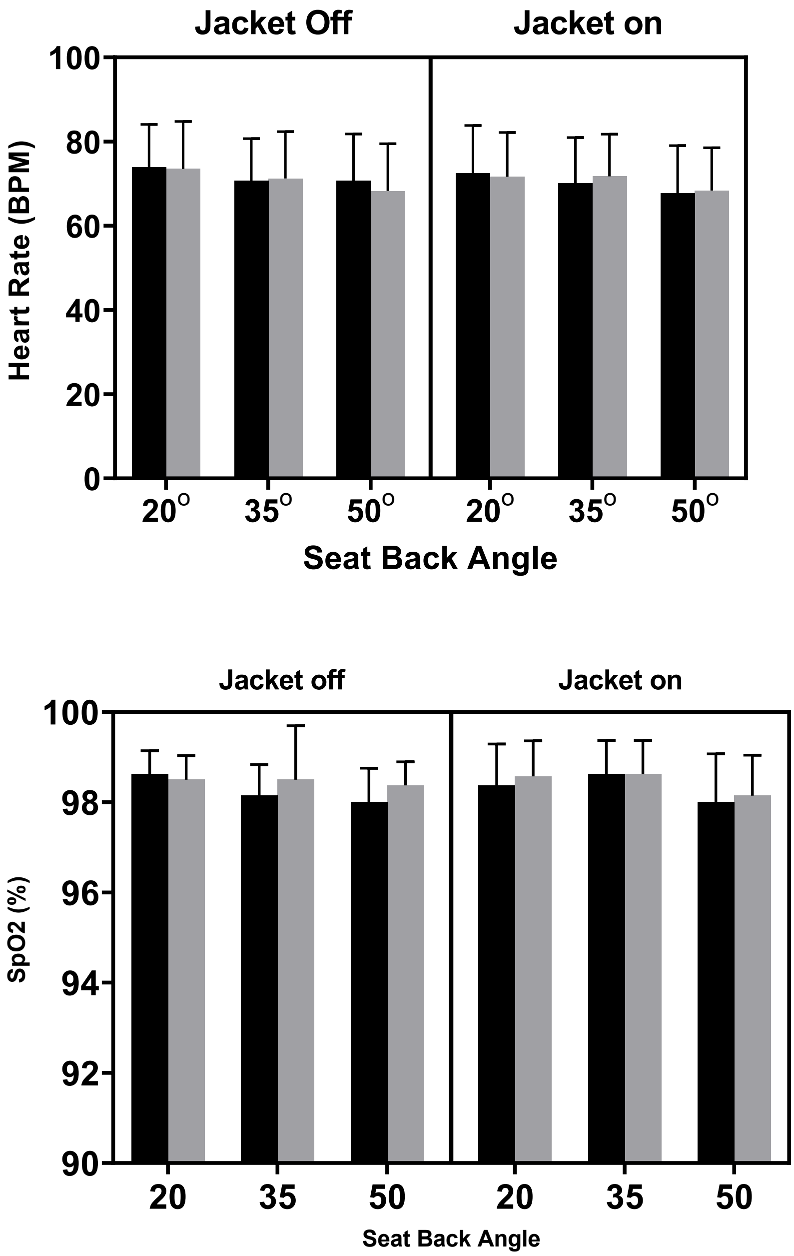

Figure 1 The graphs of cardiovascular responses of 8 healthy volunteers to the changes in the seat back angle (20, 35, 50), changes in clothing (jacket on and off) and harness (harness on or off). The black bars represent the harness off data; grey bars represent harness on data. (A) shows the heart rate in beats per minute in the last 30 seconds of a 3-minute exposure. (B) shows the oxygen saturation percentage recorded at the end of each 3-minute exposure. All data is presented as mean (SD).

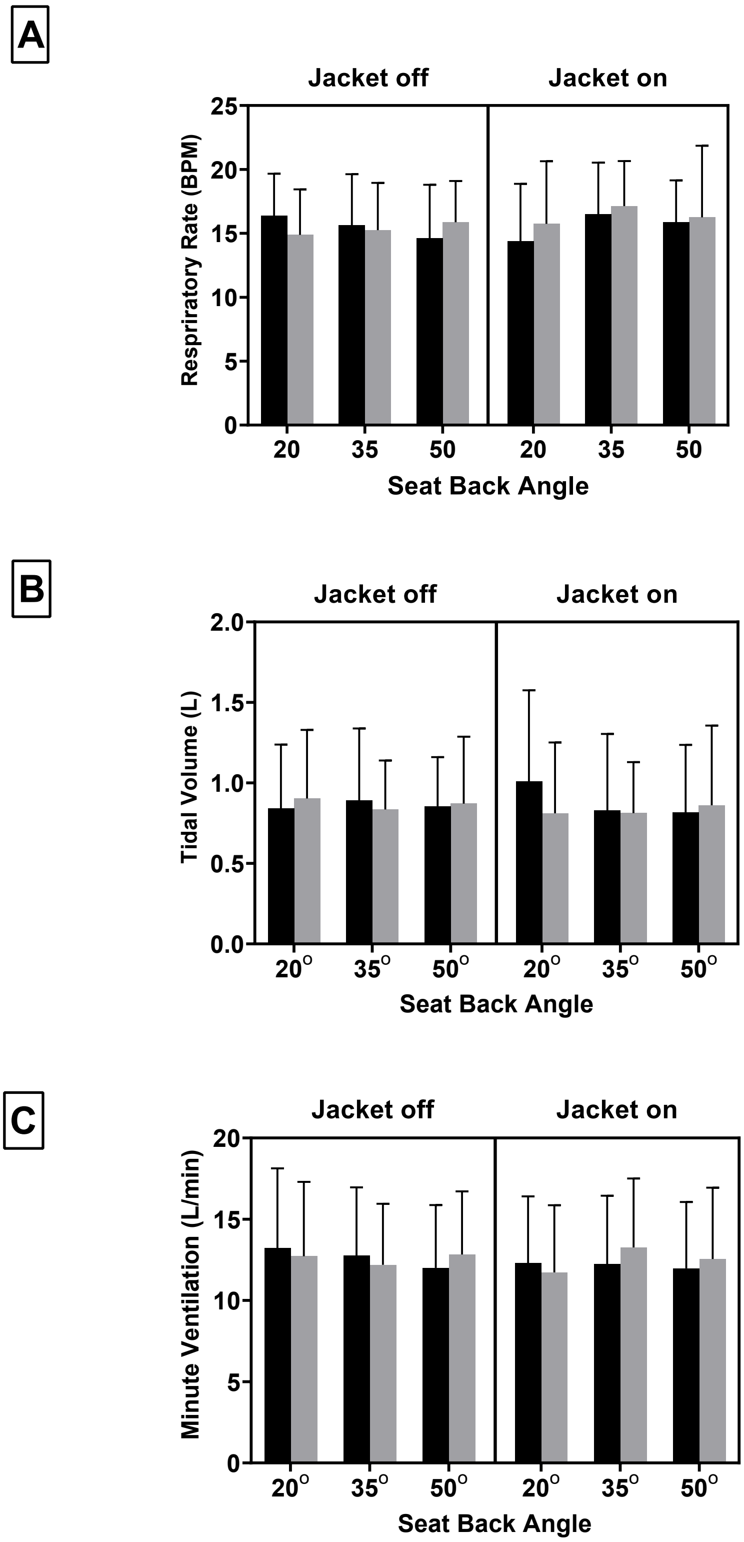

Figure 2 A graph showing "basic" respiratory responses of 8 healthy volunteers to the changes in seat back angle (20, 35, 50 degrees), changes in clothing (jacket on and off), and harness (harness on and off). The black bars represent the harness off data; grey bars represent harness on data. (A) shows the respiratory rate in breaths per minute in the last 30 seconds of 3-minute exposures. (B) shows the tidal volume in litres in the last 30 seconds of each 3-minute exposure. (C) shows the minute ventilation in litres per minute recorded in the last 30 seconds of each exposure. All data is presented as mean (SD).

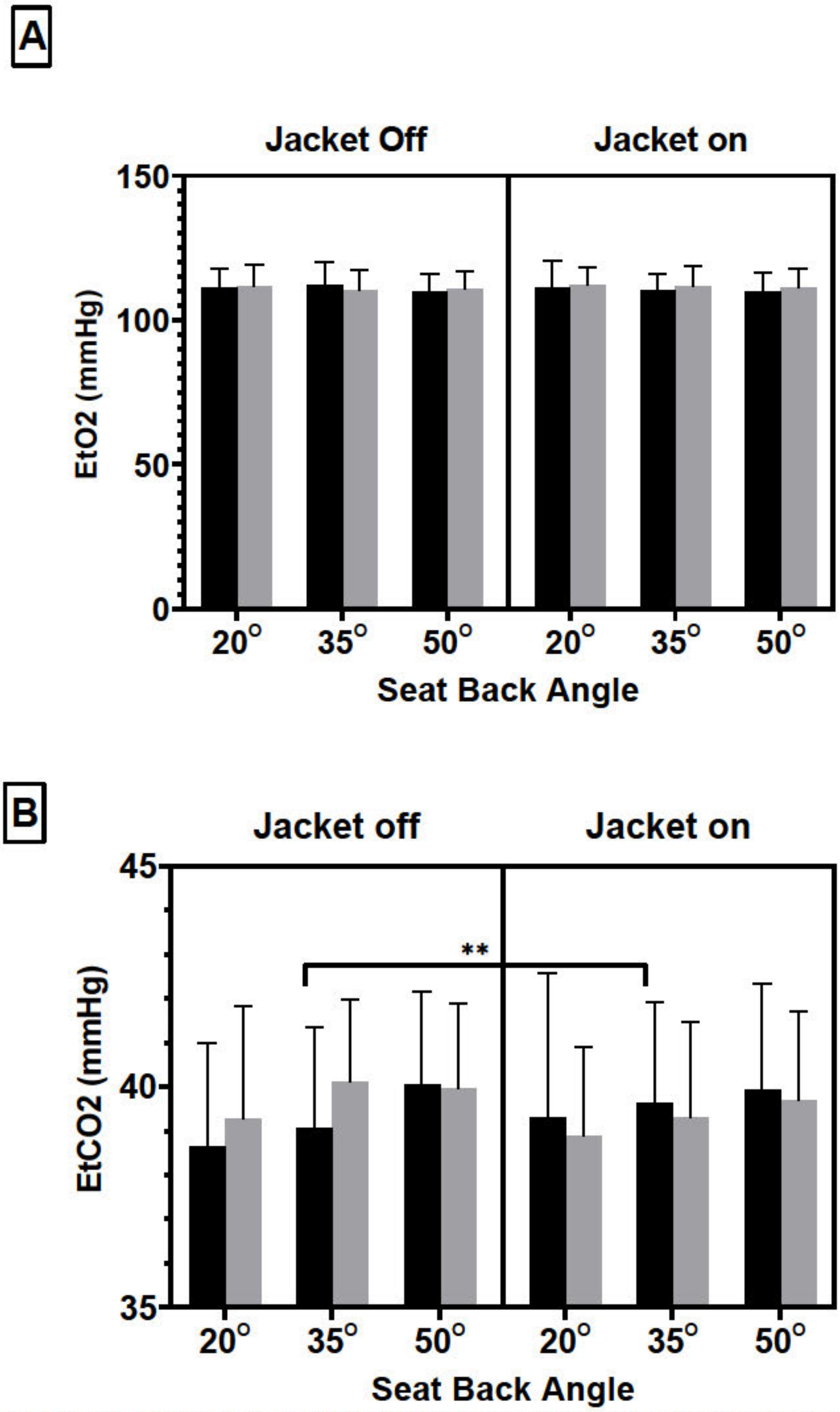

*Figure 3 Graphs showing the changes in the end tidal O2 (EtO2) and end tidal CO2 (EtCO2) of 8 healthy volunteers in response to changes in seat back angle (20, 35, 50 degrees), clothing (jacket on and off), and harness (harness on and off). The black bars represent the harness off data; grey bars represent harness on data. (A) shows the EtO2 data recorded in the last 30 seconds of each 3-minute exposure. (B) shows the EtCO2 data recorded in the last 30 seconds of each 3-minute exposure. All data is presented as mean (SD). ** signifies significant difference when compared to 35 degree jacket off with harness off (three way repeated measures ANOVA, p=0.0100, n=8).*

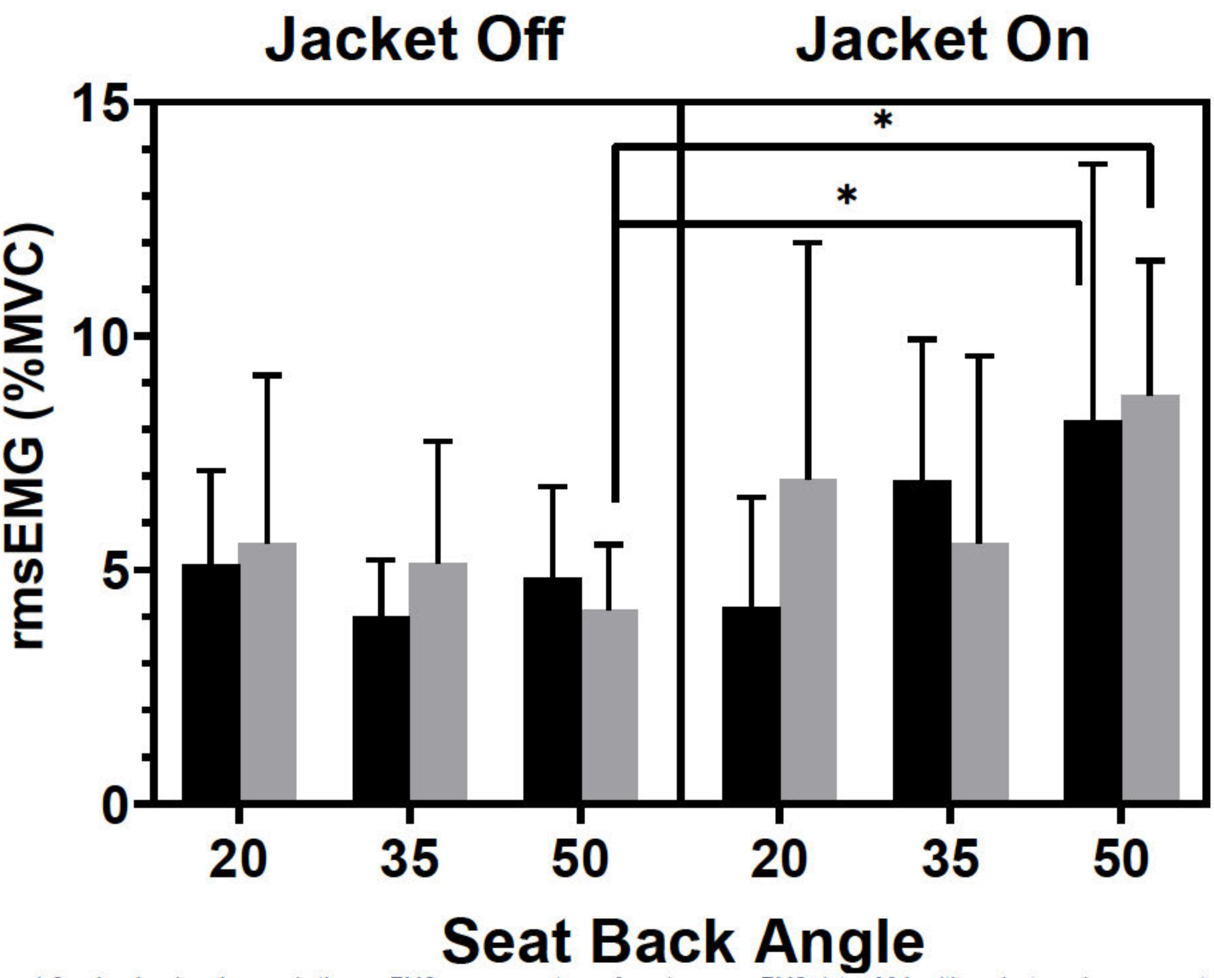

*Figure 4 Graphs showing changes in the rmsEMG as a percentage of maximum rmsEMG data of 8 healthy volunteers in response to changes in seat back angle (20, 35, 50 degrees), clothing (jacket on and off), and harness state (harness on and off). The black bars represent the harness off data; grey bars represent harness on data. All data is presented as mean (SD). * signifies significant difference compared to 50 degrees harness on, jacket off (three way repeated measures ANOVA, p<0.05, n=8).*

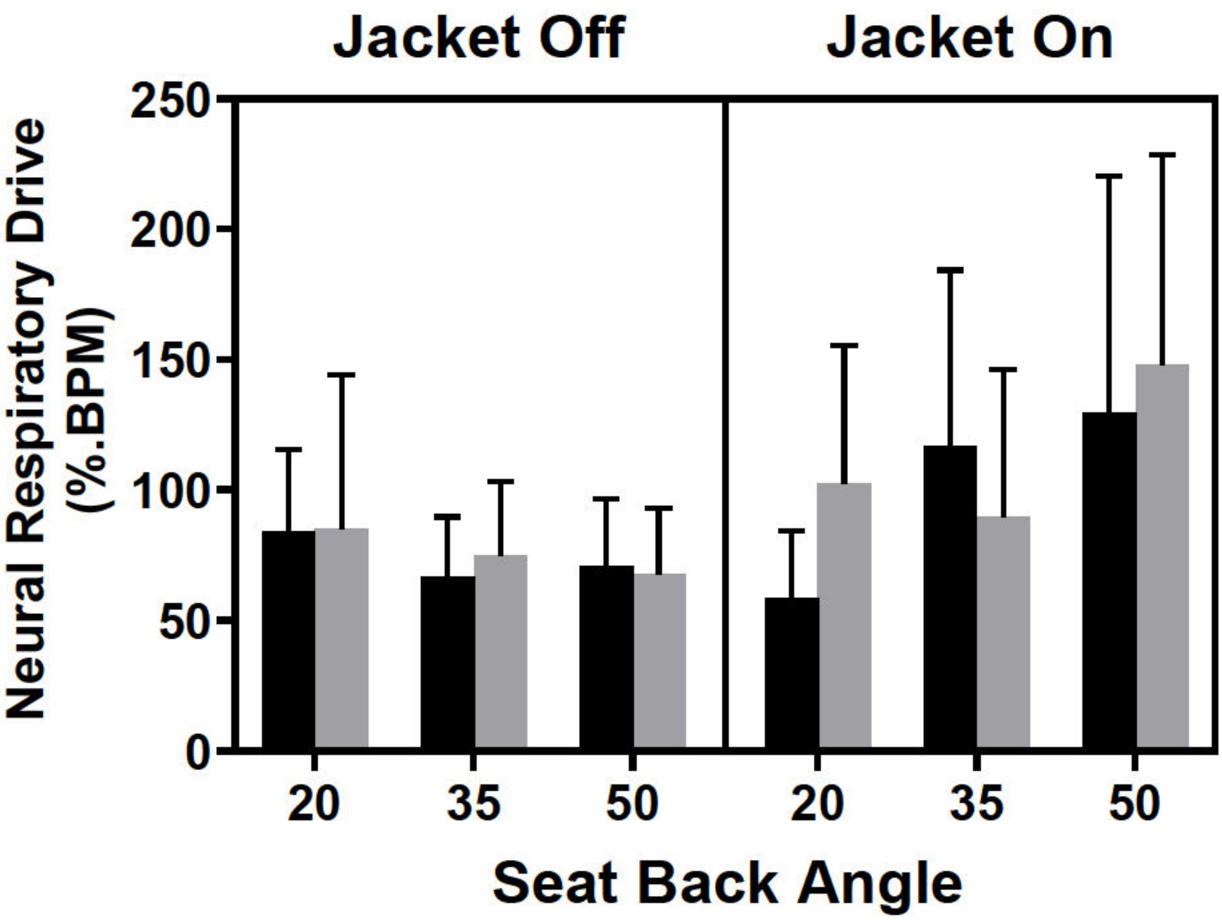

Figure 5 Graph showing changes in the neural respiratory drive of 8 healthy volunteers in response to changes in seat back angle (20, 35, 50 degrees), jacket (jacket off and on), and harness (harness off and on). The black bars represent the harness off data; grey bars represent harness on data. All data is presented as mean (SD).

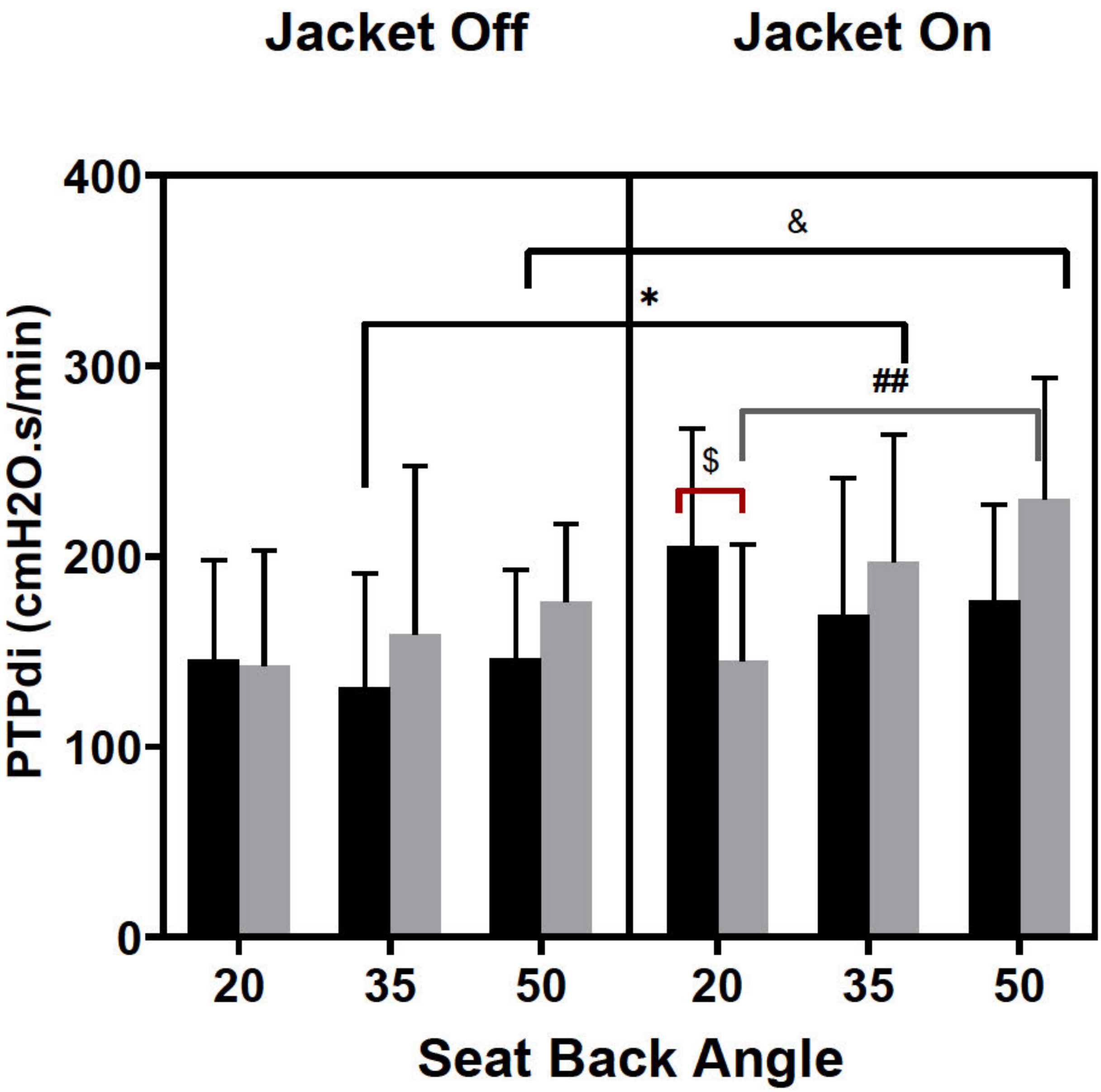

*Figure 6 Graph showing changes in PTPdi of 8 healthy volunteers in response to changes in seat back angle (20, 35, 50 degrees), jacket (jacket off and on), and harness (harness off and on). The black bars represent the harness off data; grey bars represent harness on data. All data is presented as mean (SD). * Signifies significant difference compared to 35 degrees harness off, jacket off (three-way repeated measures ANOVA, $p<0.05$, $n=8$). $ signifies significant difference compared to 20 degrees harness off, jacket on (three-way repeated measures ANOVA, $p<0.05$, $n=8$). & Signifies significant difference compared to 50 degrees harness off, jacket off (three-way repeated measures ANOVA, $p<0.05$, $n=8$). ## signifies significant difference compared to 20 degrees harness on, jacket on (three-way repeated measures ANOVA, $p<0.01$, $n=8$).*

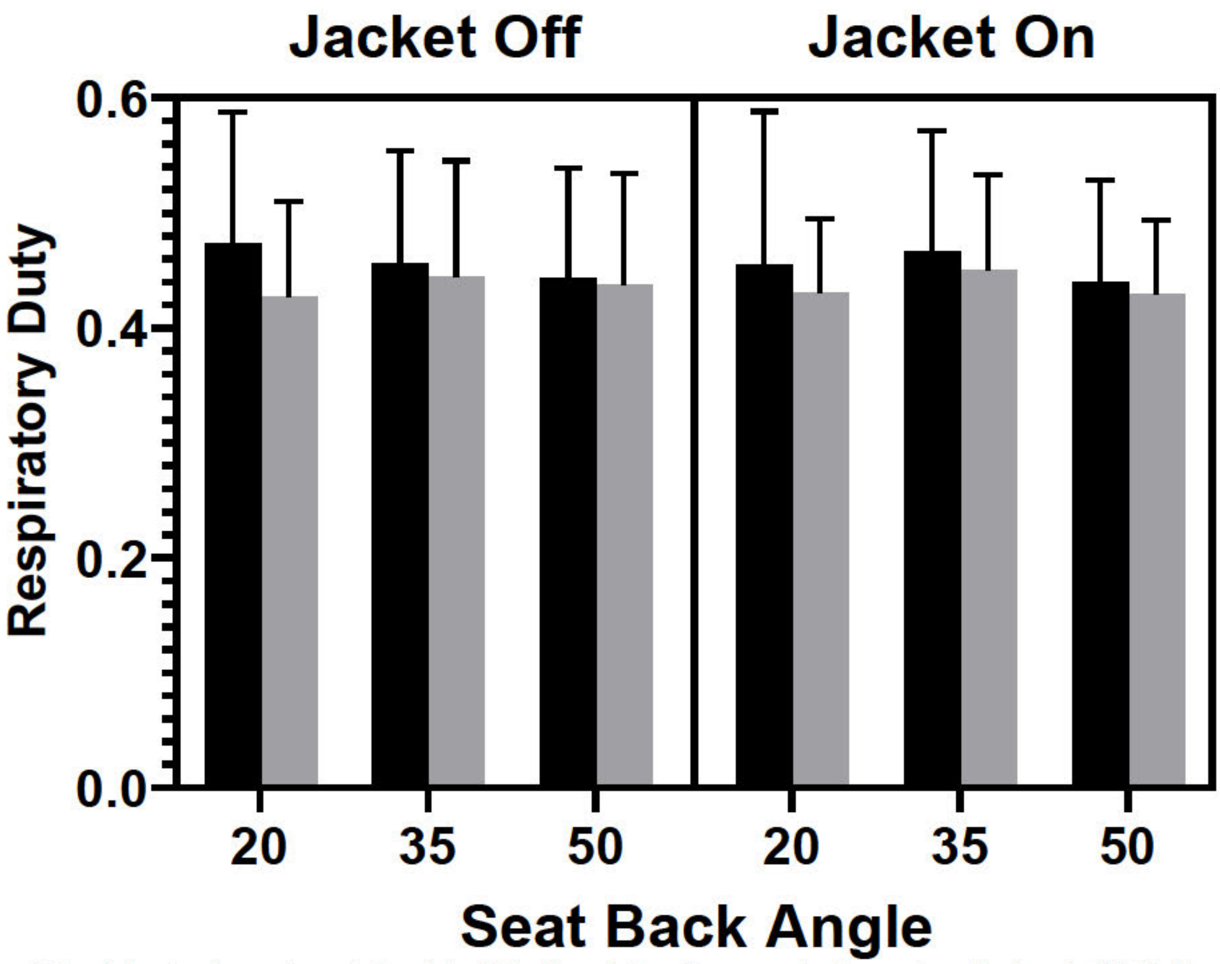

Figure 7 Graph showing changes in respiratory duty of 8 healthy volunteers in response to changes in seat back angle (20, 35, 50 degrees), jacket (jacket off and on), and harness (harness off and on). The black bars represent the harness off data; grey bars represent harness on data. All data is presented as mean (SD).

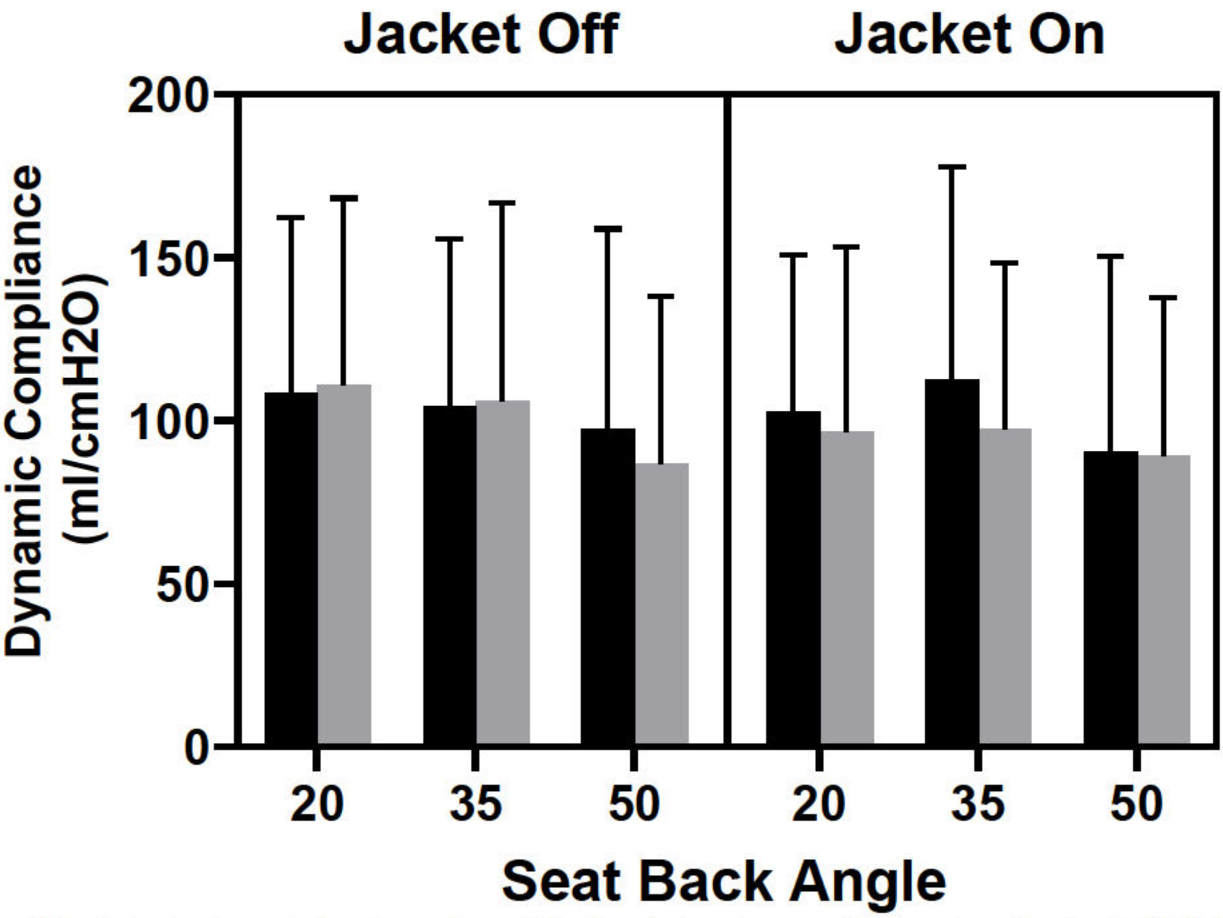

Figure 8 Graph showing changes in dynamic compliance of 8 healthy volunteers in response to changes in seat back angle (20, 35, 50 degrees), jacket (jacket off and on), and harness (harness off and on). The black bars represent the harness off data; grey bars represent harness on data. All data is presented as mean (SD).

Appendices

Appendix A: Photos

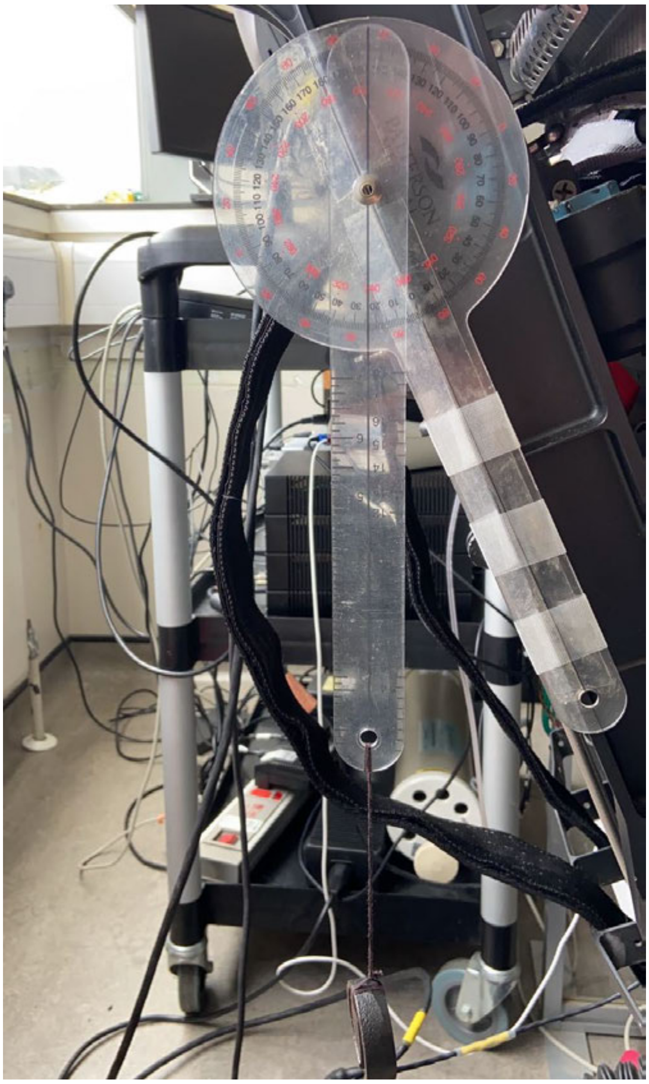

Figure 9 A photo of the protractor with a weight used to measure the seat back angle.

Figure 10 A photograph of a subject seating in the seat at 20 degrees, wearing a jacket with a harness.

Appendix B: Traces and Data Pads

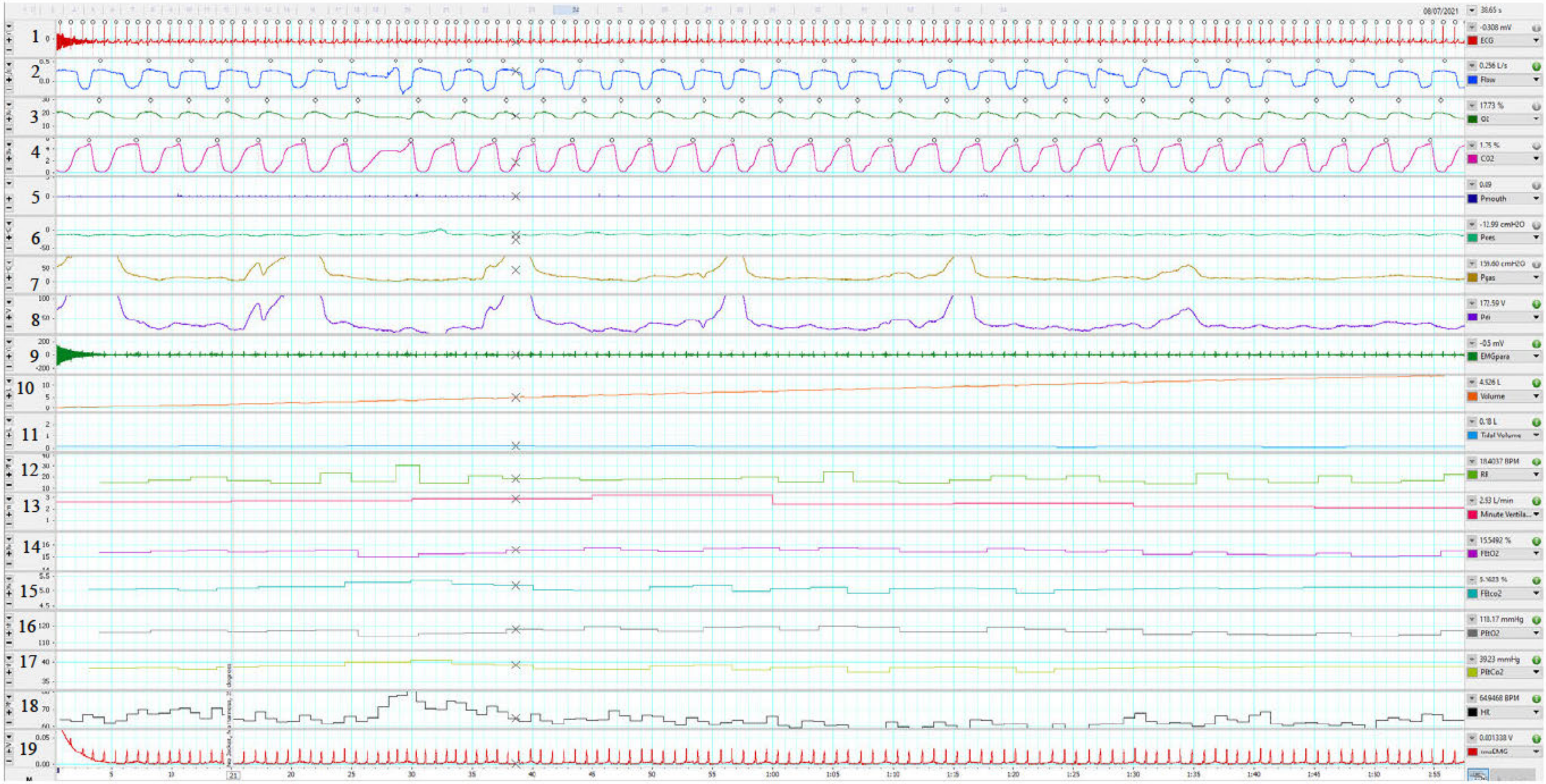

Figure 11 Screenshot of a 2-minute data recording section in LabChart showing the data recorded during testing. The channels recorded: 1) ECG (raw); 2) Flow (raw), 3) O2 percentage (raw); 4) CO2 percentage (raw); 5) Mouth pressure (raw); 6) Oesophageal pressure (raw); 7) Gastric pressure (raw); 8) Trans-diaphragmatic pressure (calculated); 9) Parasternal EMG (raw); 10) Volume (calculated); 11) Tidal volume (calculated); 12) Respiratory rate (calculated); 13) Minute ventilation (calculated); 14) Fractional end-tidal O2 (calculated); 15) Fractional end-tidal CO2 (calculated); 16) End-tidal O2 (calculated); 17) End-tidal CO2 (calculated); 18) Heart rate (calculated); 19) Root mean square EMG (calculated).

	A Block Number	B Full Comment Text	C Pdi Integral rel Start V.s	D Poes Integral rel Start cmH2O.s	E Selection Duration s	F	G Volume Maximum - Minimum L	H Poes Maximum - Minimum cmH2O
1	17	yes jacket, yes harness, 50 deg	11.89	-8.348	0.895		0.4111	13.8566
2			Pdi	Poes			Volume	Poes
3	Blk No	Cmt Text	Int (Start)	Int (Start)	Sel Duration		Max - Min	Max - Min
4			V.s	cmH2O.s	s		L	cmH2O
5	15	(start now)	10.3401	-6.9188	1.34		0.6645	10.17
6	15	(start now)	11.1718	-7.8411	1.25		0.626	11.0598
7	15	(start now)	10.4252	-6.6448	1.2225		0.6761	10.4242
8	15	(start now)	8.3794	-5.0913	1.1075		0.5867	9.7886
9	15	(start now)	9.276	-7.1813	1.365		0.6959	9.0259
10	15	no jacket, yes harness, 20 deg	8.6328	-4.9159	1.0875		0.5997	8.6445
11	15	no jacket, yes harness, 20 deg	8.2382	-4.3966	1.19		0.5847	7.8817
12	15	no jacket, yes harness, 20 deg	8.3289	-5.0526	1.1675		0.5798	8.2631

Figure 12 Screenshot of the LabChart data pad showing a sample of transdiaphragmatic pressure. Column: A - recording block number; B – full comment texts showing the condition tested; C – integral of the transdiaphragmatic pressure trace in relation to the start of selection; D – integral of the oesophageal pressure trace in relation to the start of the selection; E – duration of the selection in seconds used to calculate the respiratory duty cycle; G – range of the volume channel in the selection giving the value of tidal volume; H – range of oesophageal pressure channel in the selection.