The physiology of paragliding flight at moderate and extreme altitudes

Matt Wilkes [a] *, Martin J MacInnis [b], Lucy A Hawkes [c], Heather Massey [a], Clare Eglin [a], Michael J Tipton [a]

[a] Extreme Environments Laboratory, University of Portsmouth, Portsmouth, UK; [b] Department of Kinesiology, McMaster University, Ontario, Canada; [c] College of Life and Environmental Sciences, University of Exeter, Exeter, UK.

Corresponding Author

Dr Matt Wilkes FRCA
Extreme Environments Laboratory, Department of Sport and Exercise Science, University of Portsmouth, Spinnaker Building, Cambridge Road, Portsmouth, UK
m.wilkes@ucl.ac.uk, tel. + 44 7976 962609

Details of other authors

Dr Martin J MacInnis PhD
Department of Kinesiology, McMaster University, Hamilton, Ontario, Canada
Email. macinnm@mcmaster.ca, tel. +1 289-684-9899

Dr Lucy A Hawkes PhD
College of Life and Environmental Sciences, University of Exeter, Penryn Campus, Treliever Road, Penryn, TR10 9FE, United Kingdom
Email: l.hawkes@exeter.ac.uk, Tel. + 44 1326 259399

Dr Heather Massey PhD
Extreme Environments Laboratory, Department of Sport and Exercise Science, University of Portsmouth, Spinnaker Building, Cambridge Road, Portsmouth, UK
Email: heather.massey@port.ac.uk, Tel. + 44 23 92 843545

Dr Clare Eglin PhD
Extreme Environments Laboratory, Department of Sport and Exercise Science, University of Portsmouth, Spinnaker Building, Cambridge Road, Portsmouth, UK
Email: clare.eglin@port.ac.uk, Tel. + 44 23 92 845299

Professor Michael J Tipton PhD
Extreme Environments Laboratory, Department of Sport and Exercise Science, University of Portsmouth, Spinnaker Building, Cambridge Road, Portsmouth, UK
Email: michael.tipton@port.ac.uk, Tel. + 44 23 92 845168

Running title (37): Physiology of Paragliding at Altitude

The physiology of paragliding flight at moderate and extreme altitudes

Aims

Paragliding is a form of free flight with extreme altitude paragliding an emerging discipline. We aimed to describe the physiological demands and the impact of environmental stressors of paragliding at moderate and extreme altitudes.

We recorded oxygen consumption (VO_2), heart rate (HR), respiratory frequency (*f*R), tidal volume (V_T), oxygen saturation, accelerometry (G) and altitude in 9.3 hours of flight at moderate altitudes (to 3,073 m, n=4), 19.3 hours at extreme altitude (to 7,458 m, n=2) and during high-G manoeuvers (n=2). We also analysed heart rate data from 17 pilots (138 hours).

Results

Overall energy expenditure at moderate altitude was low (1.7 (0.6) metabolic equivalents) but physiological parameters were notably higher during take-off ($p < 0.05$). Pilots transiently reached ~7 G during manoeuvres. Mean HR at extreme altitude (112 (14) bpm) were elevated compared to moderate altitude (98 (15) bpm, $p = 0.048$). While V_T were similar ($p = 0.958$), elevation in *f*R at extreme compared to moderate altitude approached significance ($p = 0.058$).

Conclusions

Physical exertion in paragliding appears low, so any subjective fatigue felt by pilots is likely to be cognitive or environmental. Future research should focus on reducing mental workload, enhancing cognitive function and improving environmental protection.

Keywords (5): *Paragliding, altitude, extreme sports, physiology, flight*

Introduction

Paragliding began as a mountain sport in the late 1970s, when individuals inflated open parachute canopies by running down steep slopes then gliding to the valleys below (Hevesi, 2009; Poynter, 1977). Over the years, these canopies have evolved into lightweight, steerable ram-air aerofoil wings with highly complex internal structures. Harnesses have grown in sophistication to become aerodynamic cocoons with back protection, reserve parachutes and small cockpits for flight instrumentation. From a handful of enthusiasts, paragliding has become one of the most widely practiced forms of free flight. An estimated 127,000 active paraglider pilots fly worldwide (PMA, 2014).

Paragliders climb at 0.5 to 8 $m \cdot s^{-1}$, gaining altitude by flying through rising air, then gliding across country to the next source of lift (Figure 1). In addition to hypobaric hypoxia, pilots encounter acceleration (‘G’) forces, turbulence, wind, cold and exposure to UV radiation. It is cognitively demanding and subjectively exhausting: pilots must read the landscape for areas of lifting, sinking and turbulent air and calculate glide angles, while remaining sufficiently spatially aware to steer their craft though an invisible constantly-shifting, three-dimensional air mass, often containing other aircraft nearby.

Advances in paragliding equipment and in the size, skill and experience of the paragliding community have led to huge leaps in performance. From simple descents thirty years ago, flights of over 100 km are now regularly made by recreational pilots (CCI, 2017). The straight-line distance record stands at 568 km in a single flight lasting over eleven hours (FAI, 2017). High-altitude paragliding is an emerging discipline: in recent years, pilots have climbed over Broad Peak (8,051 m) without supplemental oxygen (Ewing, 2016), flown from Mount Everest and gained as much as 4,526 m of altitude in a single flight (Ewing, 2013; FAI, 2017). As they climb, pilots experience increasing hypoxia, falling environmental temperatures and may risk decompression illness from the rapid ascent (Hodkinson, 2011).

Given these stresses, along with increased speed through less dense air, it is logical to suspect that errors may increase with altitude (Taylor et al., 2015) however the physiology associated with paragliding remains largely unexplored (Wilkes et al., 2017). Research from aviation medicine would imply changes in heart rate, ventilation, vision, reaction times, working memory and mood in pilots flying above moderate (2500 m) altitudes (Petrassi et al., 2012).

Intrigued by recent flights to extreme altitudes and seeking insights to improve pilot safety and performance, we set out to define the demands of paragliding. To establish the ‘minimum’ demands of flying, we first measured the cardiorespiratory physiology of experienced paraglider pilots flying at moderate altitudes in warm, relaxed conditions. We then sought to understand how these demands might change at extreme altitudes or when undertaking high-G manoeuvres.

We hypothesised that (1) Pilots could ascend rapidly to extreme altitudes because however subjectively exhausting flying may be, the overall oxygen consumption in flight would be low i.e. less than 3 metabolic equivalents (METS) (Jetté, Sidney, & Blümchen, 1990); (2) Cardiorespiratory parameters would nonetheless be elevated at extreme altitudes compared to moderate altitudes; (3) Different phases of flight (e.g. take off and gliding) would exert distinct demands; (4) Paragliding manoeuvres would generate acceleration forces that increased the physiological load on pilots: specifically, (G_z) forces higher than +2.7, above which loss of consciousness has been previously reported (Green, 2016).

Materials and Methods

Participant Groups

We gathered data from four groups of paraglider pilots (Table 1): (1) a ‘Moderate Altitude’ group flying cross-country in warm, relaxed conditions in Laragne-Monteglin, France; (2) an ‘Extreme Altitude’ group flying cross-country in extreme altitude conditions as part of a professional expedition to the Hushe Valley, Pakistan; (3) a ‘Manoeuvres’ group undertaking manoeuvres over Lake Annecy, France; and (4) a ‘Flymaster’ group of pilots who used Flymaster Heart-G flight instruments, which allowed them to share their heart and altitude data online and to offer us a broader perspective.

Sample Selection

The four ‘Moderate Altitude’ and two ‘Manoeuvres’ pilots were selected by the authors as being capable of flying safely while wearing the bulky facemask of the Metamax 3b. The two ‘Extreme Altitude’ pilots were self-selected professional pilots taking part in the SEARCH Projects Expedition to the Hushe Valley (https://www.searchprojects.net/). Both had previously flown above 6000 m and neither were taking medication. Both were partially acclimatised: the first spent 14 days sleeping at 3,220 m and walking intermittently to 4000 m prior to the recorded flights; the second pilot had more limited opportunity for acclimatisation. The ‘Flymaster’ data was drawn from the Flymaster Live database (https://lt.flymaster.net/?feed=0). There were 224 flights with heart rate data in the database on 23 January 2017, shared by 35 pilots. The data were screened for quality and completeness, leaving 135 flights from 18 pilots. We then selected all flights of longer than 20 minutes duration (81 flights, 17 pilots), to exclude those flights where the pilots took off and glided straight to landing (‘top-to-bottom flights’), making the data more comparable to the cross-country flights of the other study groups.

Definitions of flight phases

Flights were manually divided into phases for analysis. The ‘Take-off’ phase was defined as the five minutes after becoming airborne (following the last recorded footfall), and the ‘Landing’ phase was the five minutes leading to touchdown (preceding first recorded footfall). We also selected five-minute sections from two thermal climbs and two glides from each flight (midpoint in time of the thermal or glide ± 2.5 minutes). We did not use either the first climb after take-off or the final glide into landing, as they pose distinct challenges to pilots compared to those occurring mid-flight.

Ethics

The studies were approved by the University of Portsmouth Science Faculty Ethics Committee (ID SFEC 2017-051) and the University of Exeter Research Ethics Committee (ID 2016/1433). ‘Moderate’, ‘Extreme’ and ‘Manoeuvre’ participants provided informed, written consent and were asked to fly as they normally would, not altering their flight plans or intended oxygen use for the studies. All pilots used their own certified paragliding equipment (EN-B and EN-C), including helmets and reserve parachutes. ‘Flymaster’ data were available in the public domain.

Equipment

Study variables were measured using the following equipment:

Hexoskin biometric shirt

The Hexoskin (Carre Technologies Inc., Montreal, Canada) biometric shirt measured single-lead electrocardiogram (ecg), thoracic and abdominal movements via textile electrodes and stretch receptor fibres (128-256 Hz). From these, we derived heart rate (HR), respiratory rate (fR) and tidal volume (V_T), alongside indices of measurement quality. The Hexoskin contained a 3-axis accelerometer (13 bits resolution, +/-16 G, 64Hz) aligned in the coronal plane at the level of the umbilicus. The Hexoskin has been validated for light activity and resting in a variety of postures (Villar et al., 2015).

Metamax 3b Portable Metabolic System

The Metamax 3b (CORTEX Biophysik GmbH, Leipzig, Germany) provided breath-by-breath analysis of expired gases (VO_2, VCO_2) and measured ventilation (V_E) and breathing frequency (fR). The Metamax 3b was fully calibrated (barometric pressure, fixed volume and 2-point gas concentration) before each use. The Metamax 3b has been shown to be stable and accurate for up to three hours of low-to-moderate intensity exercise (Macfarlane and Wong, 2012), validated up to 5,300 m and used up to 7,950 m in mountaineers (Levett et al., 2010).

Blood oxygen saturation

Blood oxygen saturation was measured using the Pulsox 300i (Konica Minolta, Tokyo, Japan) via an ear clip sensor (Envisen International, Bridge SpO_2 Sensor, Hong Kong) at 1 Hz (accurate to ± 2% between SpO_2 70-100%).

GPS Vario-altimeters

GPS vario-altimeters are flight instruments that measure barometric and GPS altitudes, rate of change in altitude (in $m \cdot s^{-1}$, 10 cm resolution) and GPS position, recorded at 1 Hz. The ‘Moderate Altitude’ and ‘Manoeuvres’ groups used barometric altitude, calibrated against a daily surface pressure measurement (QNH), whereas the ‘Extreme Altitude’ group used GPS altitude (QNH not available).

Flymaster Heart G

The Flymaster Heart G (Flymaster Avionics Lda., São João da Madeira, Portugal) is a specific model of GPS vario-altimeter with an integrated heart rate monitor, matching altitude with heart rate at a 1 Hz resolution.

ALTOX Mk1 Supplementary Oxygen System

The two ‘Extreme Altitude’ pilots used ALTOX Mk1 (Summit Oxygen Ltd, Fleet, UK) supplementary oxygen systems on five of their six flights above 5,500 m. They were calibrated at sea level to deliver a dose of 53 mL of 100% oxygen each breath via nasal cannulae, with a nominal triggering pressure of 2.5 cm H_2O. However, they were open systems so the volume delivered also depended on the barometric pressure.

Extreme Altitude Symptom questionnaire

For each of their flights, pilots were asked to score symptoms on take-off and then recall symptoms experienced during the flight immediately on landing. Based on the Environmental Symptoms Questionnaire (ESQ) (Sampson et al. 1993), the symptoms recorded on a four-point Likert scale were: headache, nausea, breathlessness (‘worst ever’ to ‘none’); previous night’s sleep quality, energy levels, thermal comfort, decision making, coordination, reaction times, and overall performance (‘worst ever’ to ‘best ever’); confidence (‘very anxious’ to ‘very confident’), along with the presence or absence of a cough.

Data Analysis

Data were downloaded using MetaSoft Studio (CORTEX Biophysik) for Metamax 3b data, HxServices (Carre Technologies, v. 3.2) for Hexoskin data, Visi-Download (Stowood Scientific Instruments, Build 140715) for pulse oximeter data. Altimeter data were reformatted in GPS Utility (http://www.gpsu.co.uk, v5.3). All data were imported into R Studio (Version 1.0.143, using R, R Core Development Team, version 3.3.2), synchronised using a custom R script on a 1 Hz time base, and divided up into flight phases of equal length (see 'Definitions of flight phases' above). Summary statistics, tests and plots were also conducted in R.

Descriptive statistics are reported as mean (standard deviation [SD]) with significance set as $p < 0.05$. Boxplots: boxes denote interquartile range (IQR), solid horizontal bars show median value and whiskers show data range (with individual values beyond 1.5 IQR plotted as single dots). The notches in the sides of the boxes approximately depict a 95% confidence interval (± 1.58 IQR / $\sqrt{n}$) and indicate statistical difference between boxes (i.e., if the notches do not overlap, the difference between medians is statistically significant).

The two 'Extreme Altitude' pilots flew three flights each, whereas due to weather and time constraints the four 'Moderate Altitude' pilots only had the opportunity to fly one each. This made a total of ten flights from six pilots. In the boxplots, we present the data from all ten flights. However, for the statistical tests that directly compared the 'Moderate' and 'Extreme' altitude groups, we included only one flight from each of the two 'Extreme Altitude' pilots (their flights to peak altitude). In so doing, each of the six individual pilots contributed the same number of data points to the statistical comparisons. Because of our small sample size, we used the non-parametric Kruskal-Wallis (inter-group) and Friedman (intra-group) tests followed by Dunn's Test of Multiple Comparisons (with Holm correction) to compare values between flight phases.

Results

'Moderate Altitude' Group

Four pilots flew a total of 9.3 flying hours (mean flight duration 142 (35) minutes) in warm, relaxed conditions (mean take-off temperatures 29 (1.4) ºC, Meteo Balise [Chabre]). Sleeping and baseline testing altitude was 735 m, mean and peak flying altitudes were 2236 (417) m and 3073 m respectively.

Baseline oxygen consumption (Figure 4A: VO_2, averaged over 30 seconds) was 3.9 (0.8) $mL \cdot kg^{-1} \cdot min^{-1}$. The mean VO_2 was significantly higher in the take-off phase (10.2 (3.9) $mL \cdot kg^{-1} \cdot min^{-1}$) than at baseline ($p = 0.002$); however, oxygen uptakes measured during thermal (6.0 (1.5) $mL \cdot kg^{-1} \cdot min^{-1}$), glide (5.6 (1.8) $mL \cdot kg^{-1} \cdot min^{-1}$) and landing (6.2 (1.8) $mL \cdot kg^{-1} \cdot min^{-1}$) phases were not statistically significant from one another, baseline or take-off. The overall energy expenditure of paragliding flight at moderate altitude by experienced pilots flying in warm, relaxed conditions was 1.7 (0.6) metabolic equivalents (METS) or 5.8 (2.1) $mL \cdot kg^{-1} \cdot min^{-1}$.

Heart rates (HR) were highest during the take-off phase, with the mean HR in flight being statistically elevated compared to baseline ($p = 0.005$) but not the other phases. To indicate whether the high take-off HR reflected an increase in cardiac output, we calculated mean oxygen pulse (VO_2 divided by HR), a surrogate of stroke volume (Crisafulli et al., 2007), during take-off and compared it to the mean oxygen pulse during the remaining phases of flight (Figure 5D). Oxygen pulse was significantly elevated in the take-off phase compared to during the remainder of the pilots' flights ($p < 0.001$).

Minute ventilation (V_E), fR and V_T were all significantly elevated during the take-off phase compared to baseline ($p = 0.013$, $p = 0.028$, $p = 0.049$ respectively) but not compared to the other flight phases (Figure 5).

‘Extreme Altitude’ Group

Two pilots flew a total of 19.3 hours (mean flight duration 194 (52) minutes). Sleeping altitude was 3048 m, peak flying altitude was 7458 m and mean altitude was 5270 (780) m. The pilots did not monitor environmental temperature, but the standard atmospheric temperatures at 5,200 m and 7,500 m are -18 ºC and -32 ºC respectively ((ISO), 1975).

HR, V_E, V_T and *f*R were again highest at take-off, but unfortunately no baseline data were available for comparison in this group due to logistical constraints while on the expedition. The pilots’ pulse oximetry values were recorded as between 77 and 100%; however, these data were extremely variable and 74% were discarded on inspection of quality flags indicating movement artefacts (27% of data points), light ingress to the sensor (17% of data points) and probe connection problems (23% of data points).

Regarding symptoms, one pilot reported subjective decrements in energy levels (from 3/4 to 2/4), decision making (3/4 to 2/4), coordination and reaction times (3/4 to 1/4) in his highest flight only, during which he felt at his ‘coldest ever’ (peak altitude 7458 m with supplemental oxygen above 5,500 m). The other pilot reported exacerbation of existing nausea (from 2/4, to 1/4), breathlessness (3/4 to 2/4) and reduced energy levels (3/4 to 2/4) in his highest flight only (peak altitude 6748 m, oxygen above 6,000 m). Neither pilot suffered a cough and both rated their in-flight performances positively (all 3/4).

‘Extreme Altitude’ vs. ‘Moderate Altitude’

HR at ‘Extreme Altitude’ were significantly higher than those in the ‘Moderate Altitude’ group ($p = 0.048$) (Figure 5B); however, while there was no significant difference in V_E ($p = 0.114$) or V_T ($p = 0.958$) between the two groups, the elevation in respiratory frequencies in ‘Extreme Altitude’ pilots compared to ‘Moderate Altitude’ pilots approached significance ($p = 0.058$) (Figure 4E and 4F).

‘Flymaster’ Group

Seventeen pilots flew a total of 138 flying hours (mean duration 157 (103) mins). Mean and maximum flying altitudes were 1617 (815) m and 3886 m respectively. Mean HR in the take-off phase were calculated for each pilot and plotted alongside the ‘Moderate’ and ‘Extreme’ altitude groups in Figure 5C. The results followed a similar course of very high HR in the minute following take-off before settling during the remainder of the take-off phase.

‘Manoeuvres’ Group

The two pilots completed six flights, undertaking a series of well-described paragliding manoeuvres including spiral dives, wingovers, infinite tumbles and full stalls (described in Sanderson, 2012) The most significant forces were generated during the infinite tumble manoeuvre (G_x +3.94, G_y +2.34, G_z -6.69, peak 30-second average VO_2 was 31 $mL\cdot kg^{-1}\cdot min^{-1}$, as a ‘tumbling’ manoeuvre, peak G_z was negative). However, these forces were transient, lasting less than 1 second at a time. Three spiral dives, sustained for 18, 39 and 47 seconds, at approximately 10 $m\cdot s^{-1}$ of descent rate generated maximum accelerations of G_x +1.92, G_y -2.96, G_z +4.63, and a peak 30-second average VO_2 of 17 $mL\cdot kg^{-1}\cdot min^{-1}$.

Discussion

We sought to understand the demands of paragliding flight, both to improve pilot safety and performance and to shed light on recent feats of extreme altitude flying. Across different datasets, we assessed oxygen consumption, cardioventilatory responses and forces of acceleration. In our metabolic studies, we tested experienced pilots flying in warm, relaxed conditions at moderate altitudes, to define the ‘baseline’ demands of paragliding. Oxygen consumption, heart rate, and ventilation were only statistically elevated above rest during the take-off phase. Our ‘Extreme Altitude’ and ‘Manoeuvres’ studies offered insights into how different flying situations might increase stress. Heart rates were significantly higher at extreme altitude compared to moderate altitude, and pilots experienced sustained acceleration forces of ~3 G during spiral dives and transient acceleration forces of ~6-7 G during acrobatic manoeuvres. The incorporation of data from 17 additional ‘Flymaster’ pilots of all skill levels added a wider perspective to our analysis of heart rate responses at take-off.

To a spectator, paragliding may seem like a terrifying run off a cliff, followed by sitting in a deckchair with a pleasant view. In fact, take-off is usually a gentler process: the pilot first uses the wind to launch the wing into the air above them, then takes a few steps forward and is lifted off the ground (rather than falling). Equally, while paragliding does involve limited physical movement, pilots commonly land with a feeling of subjective exhaustion. It may therefore come as a surprise to practising pilots to learn of the high heart rates measured during take-off and the overall low energy cost of the remainder of the flight.

In the five minutes following take-off, the participants experienced relatively high heart rates, a spike in oxygen pulse and increased respiratory frequency. The highest values were seen in the ‘Flymaster’ group, where skill levels were unknown, followed by the ‘Extreme Altitude’ group (n.b., the lower air density at altitude requires a faster take-off run to generate equivalent airspeed to lift off). The ‘Moderate Altitude’ group had lower heart rates, but all groups followed a similar pattern across flight phases. Take-off may be a source of anxiety for beginners and experienced pilots may feel a social pressure to succeed: fellow pilots are watching and there is a keen incentive not to waste time by failing to launch cleanly. Studies of novice and expert parachutists have demonstrated similar increases in heart rate, as well as cortisol levels in anticipation of jumping (Hare, Wetherell, & Smith, 2013). These responses do not appear to habituate with experience and even though experts may report less anxiety than novices, the physiological responses to parachuting do not appear to change (Allison et al., 2012). It has also been noted that high levels of sympathetic activation can impair working memory and safety performance in parachutists (Leach and Griffith, 2008). Given that a high proportion of paragliding accidents occur during take-off (Canbek et al., 2015; Rekand, 2012), if a similar process of anticipatory sympathetic activation is occurring in paraglider pilots as in parachutists, even experienced paraglider pilots may benefit from relaxation exercises prior to launch (Dawson et al., 2014; Pelka et al., 2017) and pre-flight checklists to mitigate potential deficits in working memory (Winters et al., 2009).

VO_2 values were higher at take-off and landing than in mid-flight. The slightly higher VO_2 values during thermalling compared to gliding, though not statistically significant, were ecologically plausible, as thermalling requires some isometric effort to keep the paraglider turning in a circle in the rising air. The overall VO_2 of flying paragliders at moderate altitudes was approximately 1.7 (0.6) METS, an energy expenditure similar to driving a car (Jetté, et al., 1990). It is therefore likely that any exhaustion felt following a long paragliding flight occurs by a similar mechanism to tiredness following a long drive: a mix of cognitive fatigue and perceived, rather than actual physical exertion (Ishii et al., 2014; Van Cutsem et al., 2017). Flying in stressful, hypoxic, very cold or very hot conditions may increase the energy expenditure of flying paragliders from our measured ‘baseline’ (Baumeister and Vohs, 2016; Doubt, 1991; Mizuno et al., 2011) but the low oxygen consumption of paragliding in general may explain much of the recent feats of extreme altitude flying.

A recent review by Tipton et al. (2017) commented that the increase in minute ventilation seen following a variety of stressors, including altitude and cold, can be achieved by an increase in either tidal volume or respiratory frequency. Increasing respiratory frequency is a less ‘efficient’ means of increasing alveolar ventilation than increasing depth, because a higher proportion of fresh gas remains in the anatomical dead space. It is therefore interesting that ‘Extreme Altitude’ pilots appeared to increase respiratory frequency rather than tidal volume during flight, in comparison to pilots at ‘Moderate Altitude’ (Figure 4E and 4F). It is hard to generalise with such a small sample; however, if this was a finding common to all paraglider pilots flying at extreme altitude then it has implications for oxygen system design: pulsed dose systems are more effective at increasing alveolar oxygenation in those with increased respiratory frequency in hypoxia, whereas continuous flow systems work better for those with predominantly increased tidal volume (Hodkinson, 2014).

High acceleration forces were achieved during the infinite tumble manoeuvre. Though impressive, these were transient peaks. The more relevant results for practicing pilots were the sustained 3-4 G forces in multiple axes (Albery, 2004), during 10 $m \cdot s^{-1}$ spiral dives, implying that loss of consciousness could occur in some individuals (Green, 2016). The paragliding ‘spiral dive’ manoeuvre is a key descent technique to avoid being involuntarily ‘sucked’ into strong clouds (Besser et al., 2007; Sanderson, 2007) and they have been investigated as a potential cause of paragliding accidents (Blok et al., 2009). Pilots should be aware of the factors that can reduce their G tolerance, which include hypoxia, low blood glucose, infection, dehydration and time away from flying (Green, 2016) and consider training in techniques known to improve cerebral blood flow during high-G situations (Kobayashi et al., 2002) especially when descending from extreme altitude.

Our studies took place in challenging environments. Consequently, they were limited by the small numbers of (only male) participants and the demands of a paragliding expedition to extreme altitude in Pakistan’s Karakorum mountains, evidenced by a lack of baseline measurements for the ‘Extreme Altitude’ group and the poor quality of the pulse oximetry data. Pulse oximetry is challenging in paraglider pilots: standard finger probes are affected by reduced perfusion, as the pilot flies with shoulders and elbows flexed above the heart. Likewise, probes attached to the toes tend to fall off during the take-off run, leaving ear probes as the best option for studies of this kind, but these proved too prone to movement artefact in our study. Equally, it is difficult to be certain of alveolar oxygenation when the pilots used open supplementary oxygen systems filled with gas from an industrial source in a developing country.

Most paragliding accidents appear to be secondary to errors of piloting or judgement, rather than equipment failure, and it remains a relatively high-risk pursuit (BHPA, 2017). Accidents tend to be severe or fatal in nature (Rekand, 2012) and Reason's 'Swiss Cheese' model – the cumulative effect of multiple small factors building up to an accident – applies to most paragliding incidents, reflecting the wider experience of general aviation (Reason, 2000; Shappell et al., 2016). Understanding the demands placed on paraglider pilots both at moderate and extreme altitudes will be key to establishing systems within the sport to prevent injury or loss of life (Schulze et al., 2002). Based on our study, these demands appear to be primarily cognitive and environmental. Future research should focus on enhancing cognitive function, reducing mental workload and improving environmental protection. Measures may include: improved checklists, instrumentation, reserve parachute design, better thermal protection and more widespread use of supplementary oxygen.

Conclusion

In conclusion, we present data from 167 hours of flight from 25 paraglider pilots. Our key findings were the low energy expenditure of flying paragliders at moderate altitudes (approximately 1.7 METs); unexpectedly elevated physiological parameters during the take-off phase and acceleration forces during manoeuvres sufficient to potentially cause loss of consciousness.

Disclosure Statement

The authors report no conflicts of interest.

Acknowledgements

Equipment for the study was provided by the University of Portsmouth Department of Sports Science, the University of Exeter Link Fund Award and Research QR uplift fund. We gratefully acknowledge the assistance of Dr Juliana Pugmire (University of Glasgow) for review of the manuscript and advice regarding statistical analysis; Professor Adrian Thomas, Professor Sue Ward, Dr Pete Hodkinson, Dr Bonnie Posselt, Dr Tom Yeoman, Dr Ellie Heath; The Free Flight Physiology Project; CASE Medicine; Escape Paragliding, Ozone Chabre Open, SEARCH Projects, Flyeo, Flymaster Avionics and all the pilots who kindly volunteered to take part.

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Tables

Table 1. Study Groups and Participants

Figure Legends

Figure 1. Phases of flight: Three-dimensional map of Laragne-Monteglin region (image from Google Earth), showing a GPS trace of a paraglider pilot in the 'Moderate Altitude' group gliding to a thermal, gaining altitude by circling in the rising air, and then gliding on across country.

Figure 2. Phases of flight: Author MW, testing the Metamax 3b in flight at 2,200 m over Laragne-Monteglin, France.

Figure 3. Cardiometabolic data for the pilots of the moderate altitude group (n = 4). Boxplots depict **(A)** VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$, 30 second average); **(B)** VCO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$, 30 second average); **(C)** Respiratory Exchange Ratio (RER, 30 second average); **(D)** heart rate (beats per minute).

Figure 4. Ventilation data for pilots in the 'Moderate Altitude' (4 pilots, 4 flights) and 'Extreme Altitude' (2 pilots, 6 flights) groups**.** Boxplots depict minute ventilation ($L \cdot min^{-1}$) for (A) 'Moderate Altitude' and (D) 'Extreme Altitude' groups; respiratory frequency ($breaths \cdot min^{-1}$) for (B) 'Moderate Altitude' and (E) 'Extreme Altitude' groups; VCO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$, 30 second average); (C) tidal volume ($mL \cdot min^{-1}$) for (F) 'Moderate Altitude' and (D) 'Extreme Altitude' groups.

Figure 5. Heart rate and oxygen pulse data from the 'Moderate Altitude' (4 pilots, 4 flights), 'Extreme Altitude' (2 pilots, 6 flights), and 'Flymaster' datasets (17 pilots, 81 flights). Boxes depict heart rate (beats per minute) for the (A) 'Moderate Altitude' and (B) 'Extreme Altitude' groups; (C) Heart rate in the take-off phase for the 'Moderate Altitude' (black line),

'Extreme Altitude' (grey line) and 'Flymaster' (dotted line) groups; and (D) Mean oxygen pulse (mL per beat, 10 second average) for the 'Moderate Altitude' group in the take-off phase (black line) and during the remaining phases of their flights (dashed line).