

The Physiology of Paragliding Flight at Moderate and Extreme Altitudes

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Abstract

Wilkes, Matt, Martin J. MacInnis, Lucy A. Hawkes, Heather Massey, Clare Eglin, and Michael J. Tipton. The physiology of paragliding flight at moderate and extreme altitudes. *High Alt Med Biol* 00:000–000, 2017.—Paragliding is a form of free flight, with extreme-altitude paragliding being 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 3073 m, $n=4$), 19.3 hours at extreme altitude (to 7458 m, $n=2$), and during high-G maneuvers ($n=2$). We also analyzed HR data from an additional 17 pilots (138 hours) using the Flymaster Live database to corroborate our findings. All pilots were male. Overall energy expenditure at moderate altitude was low [1.7 (0.6) metabolic equivalents], but physiological parameters were notably higher during takeoff ($p<0.05$). Pilots transiently reached ~ 7 G during maneuvers. Mean HR at extreme altitude [112 (14) bpm] was elevated compared to moderate altitude [98 (15) bpm, $p=0.048$]. Differences in pilots' V_T and f_R at moderate and extreme altitudes were not statistically significant ($p=0.96$ and $p=0.058$, respectively). Thus, we conclude that physical exertion in paragliding is low, suggesting that 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: altitude; extreme sports; flight; paragliding; physiology

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 (Poynter, 1977; Hevesi, 2009). 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 (Paragliding Manufacturers' Association [PMA], 2014).

Paragliders climb at 0.5 to 8 m/s, gaining altitude by flying through rising air, then gliding across country to the next

source of lift (Fig. 1). In addition to hypobaric hypoxia, pilots encounter acceleration ("G") forces, turbulence, wind, cold, and exposure to UV radiation. Paragliding 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 through 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 advanced performance. From simple descents 30 years ago, recreational pilots regularly complete flights >100 km (Cross Country International [CCI], 2017), and the straight-line distance record stands at 568 km in a single flight lasting over 11 hours (Fédération Aéronautique Internationale [FAI], 2017). High-altitude paragliding is an emerging discipline: in

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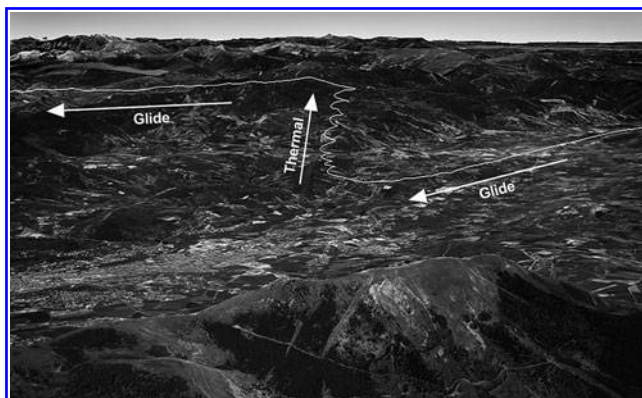


FIG. 1. Phases of flight: Three-dimensional map of Laragne-Monteglin region (image from Google Earth), showing a GPS trace of a paraglider pilot in the “Moderate Altitude” group gliding to a thermal, gaining altitude by circling in the rising air, and then gliding on across country. GPS, Global Positioning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

recent years, pilots have climbed over Broad Peak (8051 m) without supplemental oxygen (Ewing, 2016), flown from Mount Everest, and gained as much as 4526 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 (HR), ventilation, vision, as well as in cognitive demands, including reaction time, 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 physiological demands of paragliding. To establish the “minimum” physiological demands of flying, we first measured the cardiorespiratory physiology of experienced paraglider pilots flying at moderate altitudes in warm calm conditions. We then sought to understand how these demands might change at extreme altitudes or when undertaking high-G maneuvers. We hypothesized that (1) the overall oxygen consumption in flight would be low (i.e., less than three metabolic equivalents [METs]); (2) different phases of flight (e.g., takeoff and gliding) would exert varying cardiorespiratory demands; (3) cardiorespiratory parameters would be elevated at extreme altitudes compared to moderate altitudes; and (4) paragliding maneuvers would generate acceleration forces—specifically, G_z forces higher than +2.7, above which loss of consciousness has been previously reported (Green, 2016)—that increased the physiological load on pilots.

Materials and Methods

Participant groups and sample selection

We gathered data from four groups of male paraglider pilots (Table 1): (1) a “Moderate Altitude” group flying cross-country in warm calm 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 maneuvers 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.

The four “Moderate Altitude” and two “Manoeuvres” pilots were selected by the authors as being capable of flying safely while wearing the bulky face mask 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 (www.searchprojects.net/). Both had previously flown above 6000 m and neither was taking medication. Both were partially acclimatized: the first spent 14 days sleeping at 3220 m and walking intermittently to 4000 m before the recorded flights, whereas the second pilot had more limited opportunity for acclimatization. The “Flymaster” data were obtained from the Flymaster Live database (<https://lt.flymaster.net/?feed=0>). There were 224 flights with HR data in the database on January 23, 2017, shared by 35 unique pilots. The data were screened for quality and completeness, leaving 135 flights from 18 pilots. We selected all flights of longer than 20 minutes duration (81 flights, 17 pilots), to exclude those flights in which 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.

Ethical approval

The studies described herein 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.

Definitions of flight phases

Flights were manually divided into phases for analysis. The “Takeoff” phase was defined as the 5 minutes after becoming airborne (i.e., following the last recorded footfall), and the “Landing” phase was the 5 minutes leading to touchdown (i.e., preceding first recorded footfall). We also selected 5-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 takeoff or the final glide into landing, as they pose distinct challenges to pilots compared to those occurring mid flight.

Equipment

Hexoskin biometric shirt. The Hexoskin (Carre Technologies, Inc., Montreal, Canada) biometric shirt measured single-lead electrocardiogram, thoracic, and abdominal movements through textile electrodes and stretch receptor fibers (128–256 Hz). From these, we derived HR, respiratory frequency (f_R), and tidal volume (V_T), alongside indices of measurement quality. As both “Moderate” and “Extreme”

TABLE 1. STUDY GROUPS AND PARTICIPANTS

Group	Ages	Sex	Flying hours	Pilots (n)	Flights (n)	Equipment
Moderate altitude	18, 22, 35, 58	Male	>500	4	4	Hexoskin, METAMAX 3B, vario-altimeter
Extreme altitude	31, 33	Male	>2000	2	6	Hexoskin, vario-altimeter, ALTOX Mk1 >5500 m
Manoeuvres	27, 31	Male	>1000	2	6	Hexoskin, METAMAX 3B, vario-altimeter
Flymaster	30–62 ^a	Male	Unknown	17	81	Flymaster Heart-G vario-altimeter

^aMean (standard deviation)=44 (6)

altitude pilots wore Hexoskins, the Hexoskin values for respiratory frequency (f_R) and tidal volume (V_T) were used in preference to the METAMAX 3B values in the analysis to allow direct comparison between the groups. The Hexoskin contained a three-axis accelerometer (13 bits resolution, ± 16 G, 64 Hz) 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 (Fig. 2). The METAMAX 3B (CORTEX Biophysik GmbH, Leipzig, Germany) provided breath-by-breath analysis of expired gases (oxygen consumption, $\dot{V}O_2$; carbon dioxide production, $\dot{V}CO_2$) and measured ventilation ($\dot{V}_E$) and f_R . The METAMAX 3B was fully calibrated (barometric pressure, fixed volume, and two-point gas concentration) before each use. The METAMAX 3B has been shown to be stable and accurate for up to 3 hours of low-to-moderate intensity exercise (Macfarlane and Wong, 2012), validated up to 5300 m and used up to 7950 m in mountaineers (Levett et al., 2010).

Blood oxygen saturation. Blood oxygen saturation was measured using the Pulsox 300i (Konica Minolta, Tokyo, Japan) using an ear clip sensor (BRIDGE SpO₂ Sensor; Envisen International, Hong Kong) at 1 Hz (accurate to $\pm 2\%$ between SpO₂ 70%–100%).

GPS vario-altimeters. Global Positioning System (GPS) vario-altimeters are flight instruments that measure barometric and GPS altitudes, rate of change in altitude (in m/s, 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 HR monitor, matching altitude with HR at a 1 Hz resolution.

ALTOX Mk1 supplementary oxygen system. The two “Extreme Altitude” pilots used ALTOX Mk1 (Summit Oxygen Ltd., Fleet, United Kingdom) supplementary oxygen systems on five of their six flights above 5500 m. They were calibrated at sea level to deliver a dose of 53 mL of 100% oxygen each breath through nasal cannulae, with a nominal triggering pressure of 2.5 cm H₂O. 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 takeoff 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”); and confidence (“very anxious” to “very confident”), along with the presence or absence of a cough (Table 2).

Data analysis

Data were downloaded using MetaSoft Studio (CORTEX Biophysik) for METAMAX 3B data, HxServices (v. 3.2; Carre Technologies) for Hexoskin data, and Visi-Download (Build 140715; Stowood Scientific Instruments) for pulse oximeter data. Altimeter data were reformatted in GPS Utility (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), synchronized using a custom R script on a 1 Hz time base, and divided into flight phases of equal length (see “Definitions of flight phases” above). Summary statistics, tests, and plots were also conducted in R.

Descriptive statistics is reported as mean (standard deviation) with significance set as $p < 0.05$. Box plots: boxes denote interquartile range (IQR), solid horizontal bars show

TABLE 2. SYMPTOM SCALES USED TO ASSESS PARAGLIDERS’ SUBJECTIVE RESPONSES

Symptom	Lower tail	Upper tail
Headache	Worst ever	No headache
Nausea	Worst ever	Not nauseous
Breathlessness	Worst ever	Not breathless
Previous night’s sleep	Worst ever	Best ever
Energy levels	Worst ever	Best ever
Thermal comfort	Coldest ever	Hottest ever
Decision-making	Worst ever	Best ever
Coordination	Worst ever	Best ever
Reaction times	Worst ever	Best ever
Overall performance	Worst ever	Best ever
Confidence	Very anxious	Very confident

TABLE 3. COMPARISON OF KEY PHYSIOLOGICAL PARAMETERS BETWEEN GROUPS

Variable	Time	Group		
		Moderate	Extreme	Flymaster
Peak altitude (m)	—	3073	7458	3886
Heart rate (bpm)	BL	75 (2.8)	127 (10.4)	—
	TO	113 (21.1)	102 (15.4)	130 (21.2)
	TH	92 (14)	99 (18.6)	—
	GL	89 (15)	105 (18.6)	—
	LZ	97 (19.6)	—	—
f_R (breaths/min)	BL	14 (3.5)	36 (9.8)	—
	TO	28 (7.3)	23 (6.9)	—
	TH	23 (6.5)	25 (7.6)	—
	GL	19 (5.6)	30 (12.1)	—
	LZ	21 (5.3)	—	—
V_T (mL)	BL	483 (104)	863 (272)	—
	TO	879 (300)	882 (458)	—
	TH	691 (228)	845 (410)	—
	GL	806 (308)	888 (719)	—
	LZ	727 (266)	—	—
VO_2 [mL/(kg·min)]	BL	3.9 (0.8)	—	—
	TO	10.2 (3.9)	—	—
	TH	6.0 (1.5)	—	—
	GL	5.6 (1.8)	—	—
	LZ	6.2 (1.8)	—	—

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 ($\pm 1.58 \text{ IQR}/\sqrt{n}$) 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 flight each. This provided a total of 10 flights from 6 pilots. In the box plots, we present the data from all 10 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 nonparametric Kruskal–Wallis (intergroup) and Friedman (intragroup) 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 calm conditions [mean takeoff temperatures 29 (1.4) °C, Meteo Balise (Chabre)]. Sleeping and baseline testing altitude was 735 m, and mean and peak flying altitudes were 2236 (417) m and 3073 m, respectively (Table 3).

Baseline VO_2 (averaged over 30 seconds) was 3.9 (0.8) mL/(kg·min) (Fig. 3A). The mean VO_2 was significantly higher in the takeoff phase [10.2 (3.9) mL/(kg·min)] than at baseline ($p=0.002$); however, the oxygen uptake values



FIG. 2. Phases of flight: Author M.W., testing the ME-TAMAX 3B in flight at 2200 m over Laragne-Monteglin, France.

measured during thermal [6.0 (1.5) mL/(kg·min)], glide [5.6 (1.8) mL/(kg·min)], and landing [6.2 (1.8) mL/(kg·min)] phases were not statistically significant from one another, baseline or takeoff. The overall energy expenditure of paragliding flight at moderate altitude by experienced pilots flying in warm calm conditions was 1.7 (0.6) METs or 5.8 (2.1) mL/(kg·min).

HR was highest during the takeoff phase (Fig. 4A, 4B), with the mean HR in takeoff being statistically elevated compared to baseline ($p=0.005$) but not the other phases. To indicate whether the high takeoff 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 takeoff and compared it to the mean oxygen pulse during the remaining phases of flight (Fig. 5D). Oxygen pulse was significantly elevated in the takeoff phase compared to during the remainder of the pilots’ flights ($p<0.001$).

Minute ventilation (V_E), f_R , and V_T were all significantly elevated during the takeoff phase compared to baseline ($p=0.013$, $p=0.028$, $p=0.049$, respectively), but not compared to the other flight phases (Fig. 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 (Table 3). The pilots did not monitor environmental temperature, but the standard atmospheric temperatures at 5200 m and 7500 m are -18°C and -32°C , respectively (International Organization for Standardization [ISO], 1975).

HR, V_E , V_T , and f_R were again highest at takeoff, 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 artifacts (27% of data points), light ingress to the sensor (17% of data points), and probe connection problems (23% of data points).

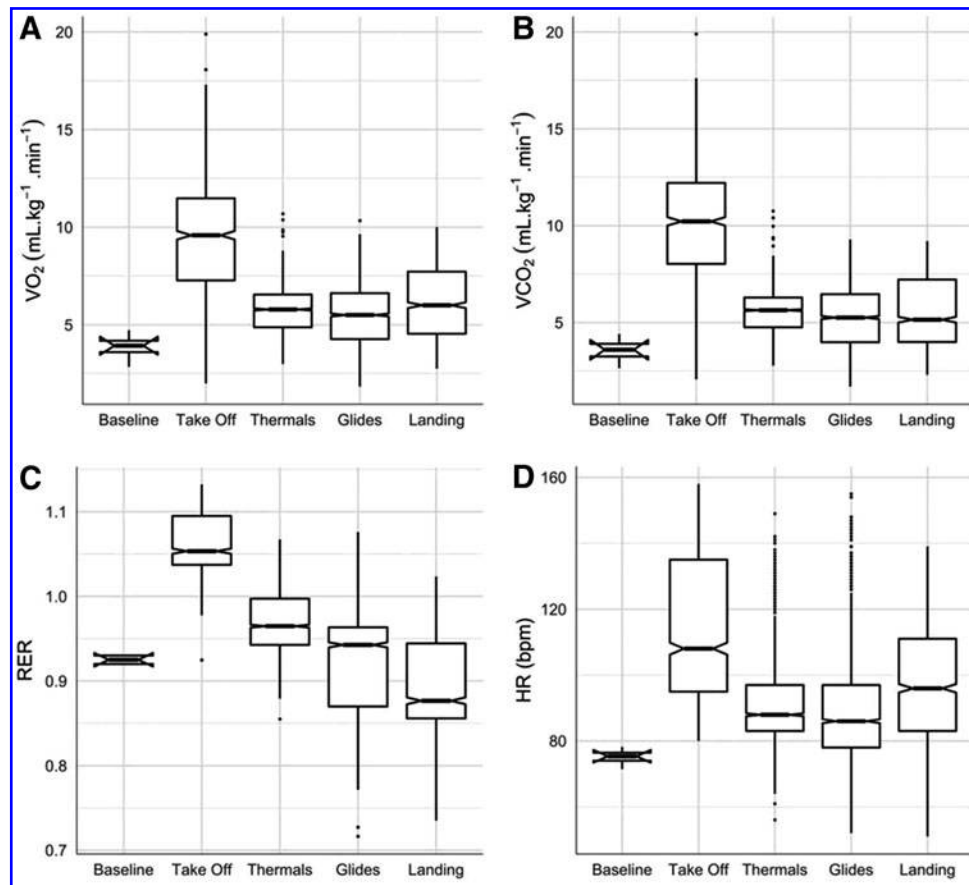


FIG. 3. Cardiometabolic data for the pilots of the moderate altitude group ($n=4$). Box plots depict (A) VO_2 [mL/(kg·min), 30 second average]; (B) VCO_2 [mL/(kg·min), 30 second average]; (C) respiratory exchange ratio (RER, 30 second average); and (D) heart rate (beats/minute).

Regarding symptoms, one pilot reported subjective decrements in energy levels (from 3/4 to 2/4), decision-making (3/4 to 2/4), and 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 5500 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 6000 m). Neither pilot suffered a cough and both rated their in-flight performances positively (all 3/4).

“Extreme Altitude” versus “Moderate Altitude”

HR at “Extreme Altitude” was significantly higher than those in the “Moderate Altitude” group ($p=0.048$) (Fig. 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 ($p=0.058$) (Fig. 4E, F).

“Flymaster” group

Seventeen pilots flew a total of 138 flying hours [mean duration 157 (103) minutes]. Mean and maximum flying altitudes were 1617 (815) m and 3886 m, respectively. Mean

HR in the takeoff phase was calculated for each pilot and plotted alongside the “Moderate” and “Extreme” altitude groups in Figure 5C and Table 3. The results followed a similar course of very high HR in the minute following takeoff before settling during the remainder of the takeoff phase.

“Manoeuvres” group

The two pilots completed six flights, undertaking a series of well-described paragliding maneuvers consisting of spiral dives, wingovers, infinite tumbles, and full stalls (described in Sanderson, 2012). The most significant forces were generated during the infinite tumble maneuver ($G_x +3.94$, $G_y +2.34$, $G_z -6.69$); however, these forces were transient, lasting less than 1 second at a time. Note that, as a “tumbling” maneuver, peak G_z was negative. During the infinite tumbling maneuver, the highest 30-second average of VO_2 recorded was 31 mL/(kg·min). Three spiral dives, sustained for 18, 39, and 47 seconds, at ~ 10 m/s of descent rate generated maximum accelerations of $G_x +1.92$, $G_y -2.96$, and $G_z +4.63$ and a peak 30-second average VO_2 of 17 mL/(kg·min).

Discussion

We sought to understand the demands of paragliding flight, both to improve pilot safety and performance and to under-

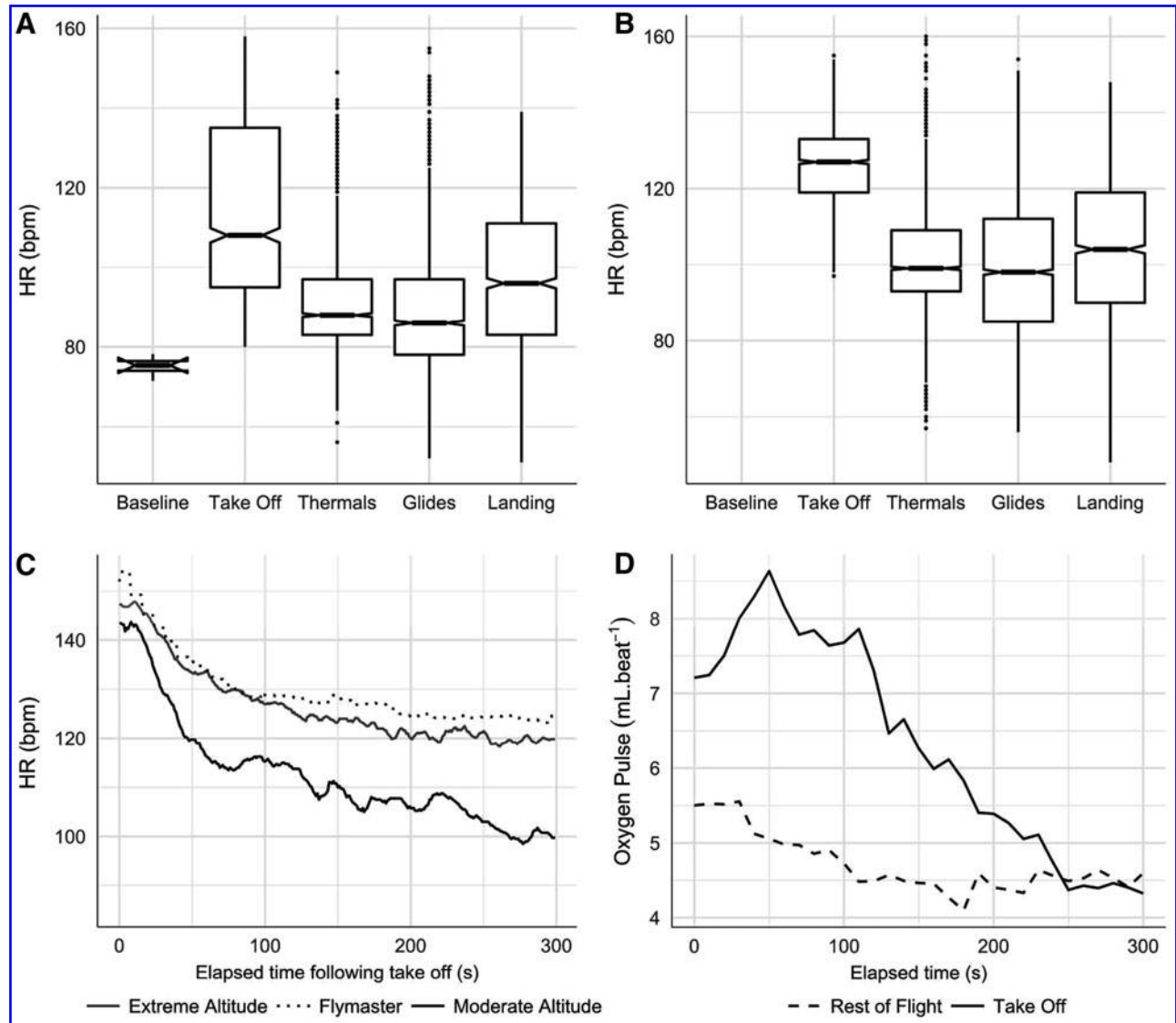


FIG. 4. Heart rate and oxygen pulse data from the "Moderate Altitude" (4 pilots, 4 flights), "Extreme Altitude" (2 pilots, 6 flights), and "Flymaster" datasets (17 pilots, 81 flights). Boxes depict heart rate (beats/minute) for the (A) "Moderate Altitude" and (B) "Extreme Altitude" groups; (C) Heart rate in the takeoff phase for the "Moderate Altitude" (black line), "Extreme Altitude" (gray line), and "Flymaster" (dotted line) groups; and (D) Mean oxygen pulse (mL/beat, 10 second average) for the "Moderate Altitude" group in the takeoff phase (black line) and during the remaining phases of their flights (dashed line).

stand recent feats of extreme altitude flying. Across different datasets, we assessed oxygen consumption, cardiorespiratory responses, and forces of acceleration. In our metabolic studies, we tested experienced pilots flying in warm calm conditions at moderate altitudes, to define the "baseline" demands of paragliding. Oxygen consumption, HR, and ventilation were only statistically elevated above the rest during the takeoff phase. Our "Extreme Altitude" and "Manoeuvres" studies offered insights into how different flying situations might increase stress. HRs 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 maneuvers. The incorporation of data from 17 additional "Flymaster" pilots of all skill levels added a wider perspective to our analysis of HR responses at takeoff.

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, takeoff 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 practicing pilots to learn of the high HRs measured during takeoff and the overall low energy cost of the remainder of the flight.

In the 5 minutes following takeoff, the participants experienced relatively high HRs, a spike in oxygen pulse (a surrogate of stroke volume), 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

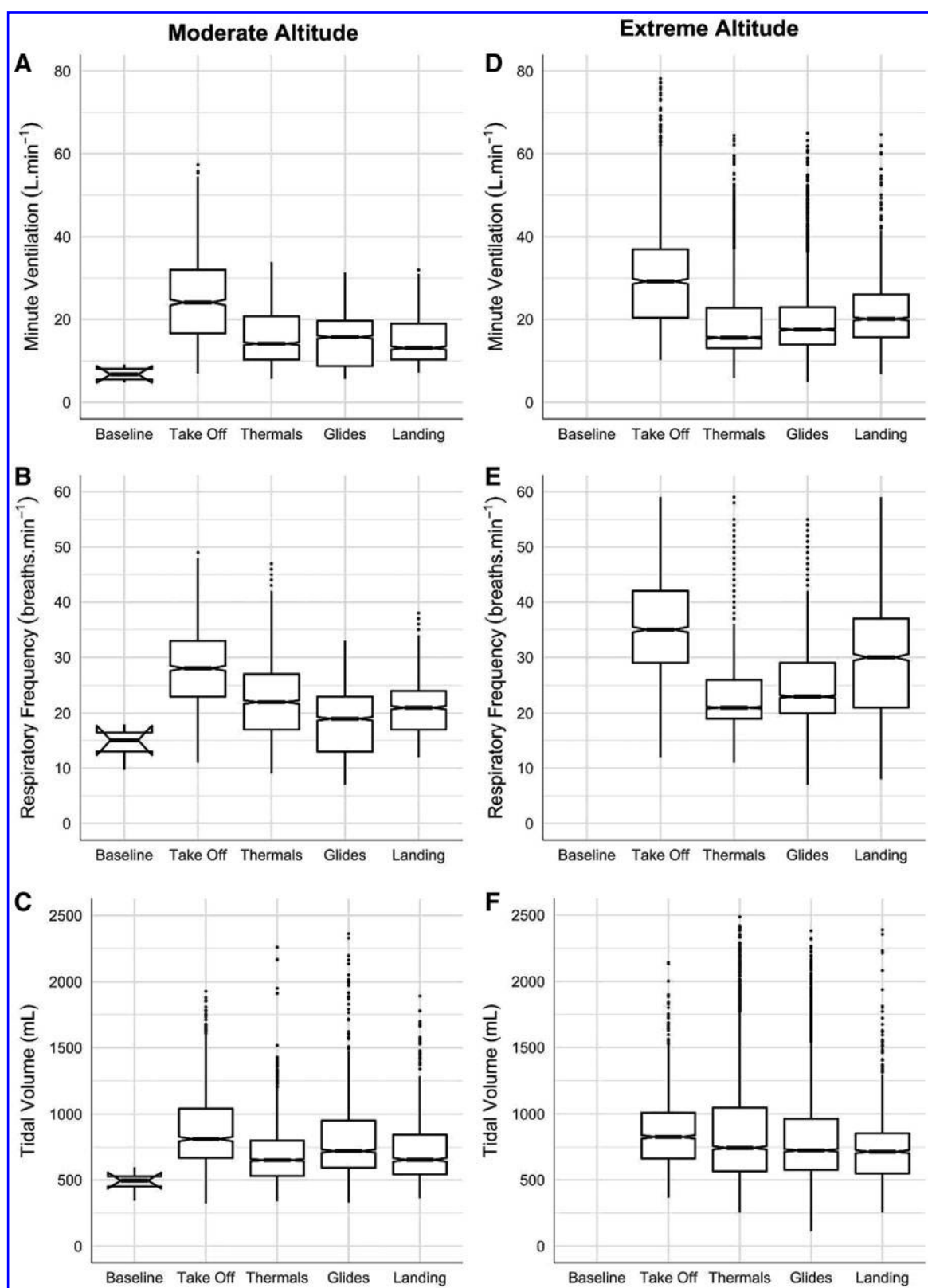


FIG. 5. Ventilation data for pilots in the “Moderate Altitude” (four pilots, four flights) and “Extreme Altitude” (two pilots, six flights) groups. Box plots depict minute ventilation (L/min), respiratory frequency (breaths/min), and tidal volume (mL/min) for “Moderate Altitude” (A–C) and “Extreme Altitude” (D–F) groups.

a faster takeoff run to generate equivalent airspeed to lift off). The “Moderate Altitude” group had lower HRs, but all groups followed a similar pattern across flight phases. Takeoff 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 HR, as well as cortisol levels in anticipation of jumping (Hare et al., 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 takeoff (Rekand, 2012; Canbek et al., 2015), 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 before launch (Dawson et al., 2014; Pelka et al., 2017) and preflight checklists to mitigate potential deficits in working memory (Winters et al., 2009).

VO₂ values were higher at takeoff and landing than in mid flight. The slightly higher VO₂ values during thermaling compared to gliding, although not statistically significant, were ecologically plausible, as thermaling requires some isometric effort to keep the paraglider turning in a circle in the rising air. The overall VO₂ of flying paragliders at moderate altitudes was ~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” (Doubt, 1991; Mizuno et al., 2011; Baumeister and Vohs, 2016), 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” (Fig. 4E, F). It is hard to generalize 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 maneuver. Although 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/s spiral dives, implying that loss of consciousness could occur in some individuals (Green, 2016). The paragliding “spiral dive” maneuver is a key descent technique to avoid being involuntarily “sucked” into strong clouds (Besser et al., 2007; Sanderson, 2007), and this maneuver has 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 takeoff run, leaving ear probes as the best option for studies of this kind, but these proved too prone to movement artifact in our study. Equally, it is difficult to be certain of alveolar oxygenation when the “Extreme Altitude” 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 judgment, rather than equipment failure, and it remains a relatively high-risk pursuit (British Hang Gliding and Paragliding Association [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 (~1.7 METs), the unexpectedly elevated physiological parameters during the takeoff phase, and the occurrence of acceleration forces during maneuvers sufficient to potentially cause loss of consciousness.

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