Paraglider Reserve Parachute Deployment Under Radial Acceleration

Matt Wilkes; Geoff Long; Rebecca Charles; Heather Massey; Clare Eglin; Michael J. Tipton

INTRODUCTION: The paragliding reserve parachute system is safety-critical but underused, unstandardized, and known to fail. This study aimed to characterize reserve parachute deployment under radial acceleration to make recommendations for system design and paraglider pilot training.

METHODS: There were 88 licensed amateur paraglider pilots who were filmed deploying their reserve parachutes from a centrifuge. Of those, 43 traveled forward at 4 G simulating a spiral dive, and 45 traveled backward at 3 G simulating a rotational maneuver known as 'SAT'. Tests incorporated ecologically valid body, hand, and gaze positions, and cognitive loading and switching akin to real deployment. The footage was reviewed by subject matter experts and compared to previous work in linear acceleration.

RESULTS: Of the pilots, 2.3% failed to extract the reserve container from the harness. SAT appeared more cognitively demanding than spiral, despite lower G. Participants located the reserve handle by touch not sight. The direction of travel influenced their initial contact with the harness: 82.9% searched first on their hip in spiral, 63.4% searched first on their thigh in SAT. Search patterns followed skeletal landmarks. Participants had little directional control over their throw.

CONCLUSIONS: Paraglider pilots are part of the reserve system. Maladaptive behaviors observed under stress highlighted that components must work in harmony with pilots' natural responses, with minimal cognitive demands or need for innovation or problem-solving. Recommendations include positioning prominent, tactile reserve handles overlying the pilot's hip; deployment bags extractable with any angle of pull; deployment in a single sweeping backward action; and significantly increasing reserve deployment drills.

KEYWORDS: paragliding, accident prevention, G force, safety systems.

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Paragliding is a growing discipline of unpowered flight, but it remains relatively hazardous.[17] It has become aviation through improvements in performance rather than safety culture. Flights of several hours are now common and the present distance record stands at 588 km in a single, 11-h, unpowered flight.[7] As in the early days of powered aviation, innovation preceded standardization and systematic work is now required to evaluate and refine safety systems, in particular the reserve parachute system.

In 2019, we conducted a study of 55 pilots deploying their reserve parachutes while descending a zipline.[26] We characterized pilots' instinctive movements, described the performance of different reserve parachute systems, and suggested changes to training and design. We noted that pilots typically reached for the reserve handles at their hip (85.1%) and tended to extract the parachute with an upwards (70.2%) rather than outwards motion.[26] These findings were relevant, as reserve handles vary in position and some harnesses are designed so the parachute can only be extracted with an outwards motion. Pilots showed evidence of freezing behavior or perseveration when faced with deployment issues.

From the University of Portsmouth, Portsmouth, Hampshire, United Kingdom, and the Rail Accident Investigation Branch, Derby, Derbyshire, United Kingdom.

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Address correspondence to: Matt Wilkes, Extreme Environments Laboratory, Department of Sports and Exercise Science, University of Portsmouth, Spinnaker Bldg., Cambridge Rd, Portsmouth, Hampshire PO1 2ER, United Kingdom; matthew.wilkes@port.ac.uk.

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The findings were largely accepted by the paragliding community and one was incorporated into the European Standard for harness design.[6] However, the primary criticism was that linear acceleration down a zipline was not representative of the majority of paragliding emergencies, which involve rotational forces. To address this, we conducted this larger study of reserve parachute systems in 88 pilots deploying from a centrifuge.

Paraglider pilots fly in a harness suspended below an aerofoil-shaped ram-air main canopy (the 'glider'). Turbulence can cause the glider to depart its normal flight configuration, typically by deflating one side of the canopy (an 'asymmetric collapse'). The pilot will almost always attempt to recover the collapse before deploying their reserve parachute. Recovery is generally preferable to reserve deployment, as it allows the pilot to continue flying. It also avoids the hazards of a descent under an unsteerable reserve parachute. However, if the main canopy cannot be recovered, the pilot must recognize this with sufficient time to deploy the reserve parachute before impacting the terrain. Accident investigations have frequently commented on the failure of paraglider pilots to deploy their reserve parachutes before impact.[23]

Once the need to deploy has been recognized, the pilot must remove their hands from the control line handles (ideally, taking them both in one hand), then locate and grip the reserve handle (**Fig. 1**). Pulling the handle away from the harness initially releases pins that hold the reserve container closed. The handle is also attached to the reserve deployment bag by a strop. So, continuing to pull the handle then pulls the deployment bag out from the now open container. The pilot throws the deployment bag away from the harness, releasing their grip on the reserve handle. The reserve parachute lines come under tension, pulling the parachute from the deployment bag (which falls away), exposing the folded parachute fabric to the airflow and opening the reserve canopy. The pilot then swings under the reserve, suspended by a reserve bridle connected to harness attachment points (usually at the shoulders). Once the reserve canopy is open, the pilot must clear any entanglement between the main and reserve canopies, disable the main canopy, and prepare for landing under the reserve.

The critical step in this sequence is making the decision to stop trying to recover the glider and to deploy the reserve.[8] This decision requires complex cognition, including cognitive

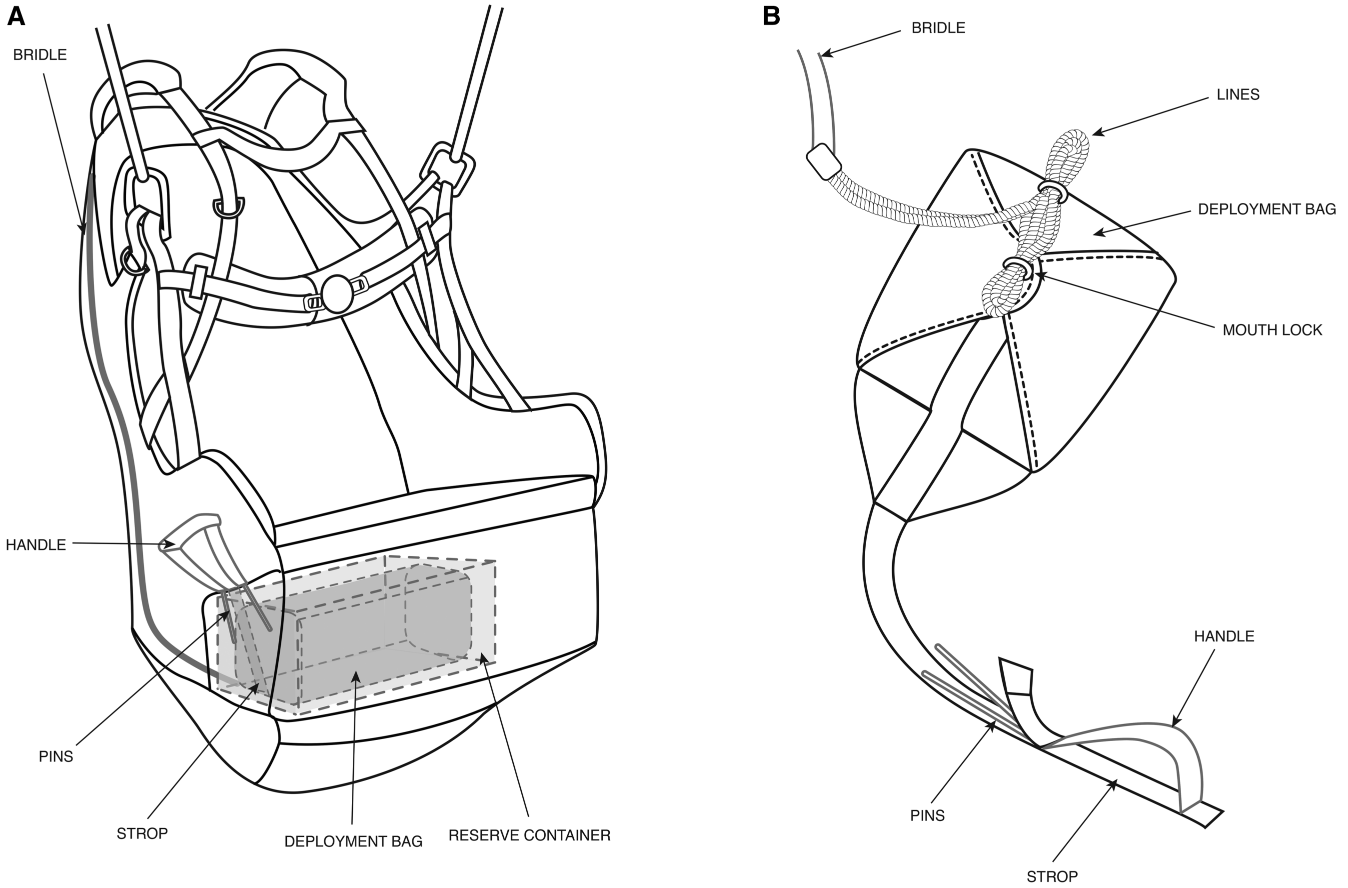

Fig. 1. A.) The deployment bag contains the reserve parachute and sits within a reserve container, closed by two pins. When the handle is pulled, the pins are removed, allowing the reserve container to open and the deployment bag to be extracted and thrown. Once the parachute inflates, the pilot hangs underneath it, connected by the bridle. The container can be mounted in front ('front-mounted system') or underneath the pilot ('underseat system', depicted above). For underseat systems, the handle is mounted on the right of the harness. B.) The parachute is contained within the deployment bag. When the bag is thrown, the lines are pulled sequentially from the mouth lock, the bag opens, the parachute deploys, and the deployment bag falls away.

switching and situational awareness, under high levels of stress. However, stress can narrow attention, reduce visual scan, limit thinking, hurry decision making, and reduce working memory capacity and retrieval.[16,22] It is consequently of paramount importance that the reserve parachute system works efficiently and instinctively. Indeed, once the decision to deploy has been made, there may be little time, altitude, or cognitive reserve left for the pilot to resolve any issues. If the situation demands choice or an innovative solution, then humans can take up to 10 s to respond, with either absent, irrational, or stereotyped responses in the interim.[15] During a paragliding emergency, 10 s can equate to hundreds of meters of lost altitude and or acceleration forces sufficient to induce loss of consciousness.[27]

At present, reserve parachute systems vary significantly, with each element potentially being made by a different manufacturer. Some elements are tested by professional test pilots prior to commercial release and some must conform to European Norm standards.[6] However, test pilots are not typical of the flying population, as they fly vastly more hours each year, with very frequent reserve deployments. Equally, the standards only cover some attributes of the reserve system. In contrast, recreational pilots fly fewer hours, deploy rarely, and receive varied (generally minimal) instruction regarding reserve deployment.[2] Such instructions can include pulling the handle either upwards or outwards, and then either throwing the deployment bag away in a single sweep or first bringing it forward then throwing it backward.[9]

In skydiving, several studies have investigated deployment forces and optimum positions of deployment handles.[1,4,14] Skydiving deployments are different to those in paragliding, as they occur at terminal velocity, in a much more constrained harness, and deployment is part of every jump rather than a rare event. In Helicopter Underwater Escape Training, lack of consistency in the position and opening mechanisms of escape hatches has been shown to reduce the chances of successful escape.[3] Some systems have been shown to be ergonomically superior to others given participants' instinctive responses under stress.[3] Developing reserve parachute systems that work in harmony with pilots' natural responses may, therefore, save time, altitude, and ultimately lives.

Unlike the linear acceleration of the zipline, radial acceleration is produced by a change in the direction of motion. There are three potential semistable rotational configurations encountered during a paragliding emergency, or deliberately induced as descent techniques or during aerobatic routines: spin, SAT, and spiral. In a spin, the center of rotation (and the vertical z-axis) is within the wing itself (**Fig. 2A**). In a SAT, it lies between the pilot and the wing (**Fig. 2B**), and, in a spiral, it lies beyond both the pilot and wing (the longest radius of rotation, **Fig. 2C**). Spins are rarely sustained for more than a few seconds and occur primarily in the yaw axis, with the G_z vector aligned with the axis of rotation. Consequently, the pilots experience minimal G_z load in spin. SATs often develop following an uncorrected asymmetrical collapse, building steadily in speed ('autorotation') until they become established. Spirals are induced by slowing one side of the glider until it is flying in a stable rotational configuration toward the ground. In SATs and spirals the G_z vector is perpendicular to the axis of rotation, generating substantial G_z loads. The ratios between angular velocities and radii of rotation in these maneuvers are such that G_z loading is typically less strong in SATs than spirals. Sustained acceleration of 2–4 G_z has been recorded during moderate paraglider spiral dives and both maneuvers can be sustained until all altitude is lost.[27] Consequently, SATs and spirals were the focus of this study.

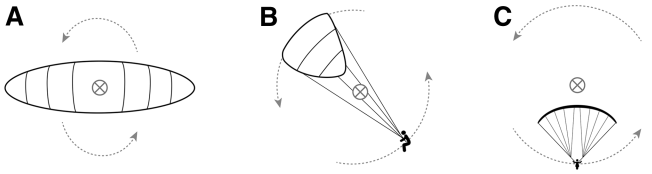

Fig. 2. A.) Spin: the center of rotation is the wing itself. B.) SAT: the center of rotation is between the pilot and wing. C.) Spiral: the center of rotation is beyond the pilot and the wing. X represents the vertical Z-axis and the center of rotation.

Sustained G_z acceleration induces significant physiological change that may ultimately result in unconsciousness.[12] In the context of a paraglider reserve parachute throw, G_z might also specifically affect the accuracy and force of arm movements, in addition to its potential for global disorientation and incapacitation.[10,13] Distortion of the harness and movement of the deployment bag within the container might also alter equipment performance. This study aimed to describe the effects of radial acceleration on the performance of paraglider pilots and reserve parachute systems during deployment. It hoped to build on the work of the previous zipline experiment to refine recommendations that would improve the chances of successful deployment. It was hypothesized that: 1) a spiral would be more disorientating than a SAT (due to higher G loading); 2) based on the previous study, participants' search for the reserve handle would begin on their hip and they would tend to pull the handle directly upwards, not outwards; and 3) there would be evidence of perseveration and freezing behavior in some participants.

METHODS

Subjects

An initial call for participants was made via the German Hang Gliding and Paragliding Federation website. Responding to the call were 240 licensed paraglider pilots, of whom 90 were selected by two senior instructors at Flugschule Hochries. The instructors were briefed to choose a broad but representative range of ages, experience, and equipment based on their knowledge of paragliding. Taking part in the experiment were 88 participants (2 self-excluded for potential COVID-19). The mean age of participants was 41.5 (10.4) yr. Of the participants, 27 were women (30.7%) and 61 (69.3%) were men; 81 (92.0%) were right-handed and 7 (8.0%) were left-handed. The participants had been flying for a median of 5 [interquartile range (IQR) 2–11] yr and flew a median of 30 (IQR 20–50) h/yr. Of the subjects, 50 (56.8%) had previously attempted a spiral dive in flight, 17 (19.3%) had executed a planned reserve parachute deployment in flight training, 4 (4.5%) from a centrifuge and 2 (2.2%) in an emergency.

The study was approved by the University of Portsmouth Science Faculty Research Ethics Committee (SFEC 2018-133A). All participants provided informed, written consent and the study complied with the Declaration of Helsinki, except for registration in a trial database. The pre-study information, briefing, consent forms, and all survey instruments were in their native language (German). Participants' faces are shown in the images with their explicit permission.

Equipment

The study used the centrifuge at Flugschule Hochries, Brannenberg, Germany. The centrifuge could generate forces of up to 7 G when turning in a clockwise direction and 3 G in an anticlockwise direction, calibrated at the back of the harness (at the approximate level of the pilot's heart). Centrifuge runs were filmed by two GoPro cameras (GoPro Inc., San Mateo, CA, USA). One was attached to the centrifuge arm to give a wide view and the other moved with the pilot to provide a close up-of the reserve handle (**Fig. 3**). Both were set to 2.7 k, 50 fps, and 'wide' field of view.

All participants used their own paragliding harness and reserve parachute system. The participants were issued with the same standardized, appropriately sized gloves as in the previous zipline experiment (Dura Gloves Etouch, DeFeet International, Hildebran, NC, USA) and asked to hold the control handles in an open 'beginner' grip to eliminate glove thickness and entanglement with the control handles as confounding factors. They were also issued with a standardized lightweight paragliding helmet to protect their necks during the run (Supair Pilot, Supair VLD, Annecy, France) (Fig. 3).

Procedure

Participants were sent information via email then given a standard briefing on the day of the study. The briefing included a demonstration of the tasks, along with the opportunity to ask questions about the study process. Participants filled out a pretest questionnaire, which included demographic and equipment details, along with measures of flying, reserve deployment, and G force experience.

Prior to deployment, participants were given a standardized task, identical to the one used successfully in the zipline study.[26] The task sought to simulate the demands of a reserve throw situation, including overwhelming and conflicting demands on executive function and working memory, cognitive switching, and motor response. Participants were asked to look up at two LED lights (Fig. 3) and, when one switched on, apply input to the control line on the corresponding side for the duration the light was on. At the same time, they were given a form of the Verbal Fluency Task that engaged executive function and working memory.[24] The task required participants to name as many different words as they could beginning with the letter 'A' (in German). After 10 s, the centrifuge began to turn. As soon as it reached the target G loading, the LED lights turned red and a buzzer sounded as a signal for the participant to deploy. Thus, at the point of deployment, participants had their hands in the control lines in their usual flying position, their gaze was directed upwards (toward their 'collapsed wing') and they were experiencing high levels of cognitive load in multiple domains, as judged by their ability to maintain both tasks simultaneously to that point. They then had to make a cognitive switch from 'fixing their wing' to deploying their reserve parachute as soon as the buzzer sounded.

Fig. 3. Participant in recumbent ('cocoon) harness in spiral configuration, looking up at the LED lights (1), with hands in the brake lines wearing standard gloves (2) and helmet (3) being filmed by cameras in wide view (4) and close-up handle view (5).

The Day 1 (*N* = 43) participants were accelerated in a clockwise direction (facing forward, Fig. 2C) to a peak of 4 G_z, simulating a spiral dive. The Day 2 (*N* = 45) participants were spun in an anticlockwise direction (facing backward, Fig. 2B) to a peak of 3 G_z, simulating a SAT. In a spiral, it took 14 s to reach 4 G from stationary and 12 s to reach 3 G in SAT. Each run was around 20 s in total, depending on how long the participant took to throw their reserve. If there were issues with deployment, then participants undertook further centrifuge runs to ensure that they could deploy successfully before leaving the study center. Only the first run was included in the quantitative analysis, but footage of any additional runs was available for the qualitative discussions.

Immediately after their centrifuge run, participants were interviewed by a bilingual German/English speaking investigator and paraglider pilot. They were asked to rate their experience in six domains (anxiety, engagement with the task, disorientation due to G forces, and their feelings of instinctiveness, ease, and effectiveness of the deployment) using a five-point categorical scale (1 = "Not at all", 2 = "Slightly", 3 = "Moderately", 4 = "Very", 5 = "Completely"). They were asked specific questions on whether they experienced any G force symptoms or attempted any anti-G techniques, and to comment freely on their centrifuge run. The interviews lasted approximately 10 min, during which the investigator made notes, then she immediately translated their responses into English before interviewing the next participant.

Analysis

The video footage was edited, analyzed, and reviewed in Objectus Studio (v. 1.0.2, Objectus Technology LLC, Philadelphia, PA, USA). The footage was then reviewed separately by two subject matter experts, an ergonomist and a senior paragliding instructor, and then discussed via Zoom (Zoom Video Communications Inc.). The online discussions were organized thematically, ordered by: 1) pilot behavior; 2) equipment performance; 3) differences between zipline, spiral, and SAT studies; 4) recommendations for training, practicing pilots, and manufacturers; and 5) future work. Comments were iteratively coded, analyzed thematically, and summarized for presentation.

Analysis was conducted using R Studio (Version 1.0.143, R Core Development Team, version 3.4.1). Distribution of results was assessed using descriptive methods (skewness, outliers, and distribution plots) and inferential statistics (Shapiro-Wilk test). Where the outcome of the Shapiro-Wilk test was significant, nonparametric tests (typically, Wilcoxon rank sum and Spearman's rank correlation) were used instead. Multiple comparisons were corrected using the Holm-Bonferroni method. Associations between categorical variables were tested using Pearson's Chi-squared test for independence. Significance was set at $P < 0.05$. The different harness and reserve parachute combinations were assigned to four categories for grouped comparisons: 'seated harness, underseat reserve' (54, 61.3%); 'seated harness, front-mounted reserve' (7, 8.0%); 'cocoon harness, underseat reserve' (23, 26.1%); and 'cocoon harness, front-mounted reserve' (4, 4.5%).

RESULTS

Of the 88 participants, 86 (97.7%) were able to successfully deploy their reserve parachute before termination of their centrifuge run. Of the two who failed, one had an older harness with a known safety issue, while the other 'froze' and did not attempt deployment. Deployment times were heavily right-skewed. The times for successful deployments are given in **Table I**. There were no significant differences in deployment times between spiral and SAT configurations ($P = 0.773$).

The numbers of participants able to continue both the verbal and physical tasks, one, or neither until the deployment signal are given in **Table II**. In the interviews following their centrifuge runs, 71 (80.6%) stated they were "completely" or "very" concentrated on the tasks before the signal to deploy. There were no significant differences between spiral and SAT for task completion [χ^2(3 df, $N = 88$) = 0.94, $P = 0.815$] or task focus scores ($P = 0.832$).

In the postrun interviews, 39 (44.3%) stated they were 'not at all', 23 (26.1%) 'slightly', 15 'moderately' (17.0%), and 11 (12.5%) 'very' disorientated by the acceleration forces. There were no significant differences between spiral and SAT for disorientation scores ($P = 0.986$). Reported symptoms of acceleration felt by participants were pressure (15.9%), dizziness (14.7%), impaired concentration (11.4%), disorientation (10.2%), nausea (5.7%), and peripheral visual loss (4.5%). The majority (66, 75%) of participants did not try to actively counter the acceleration forces, though 16 (18.1%) attempted some form of isometric muscular contraction and 6 (6.8%) some form of modified breathing technique.

The majority of participants (62, 70.5%) maintained their gaze in a forward direction throughout the deployment. There were 20 (22.7%) who looked toward the reserve and 6 (6.8%) who looked toward the reserve only after initially struggling to locate the handle by touch alone.

The participants' hand positions when signaled to deploy depended on whether or not they were in spiral or SAT, and whether they had been more focused on the physical or verbal tasks. For those in spiral, 15 (34.9%) attempted the tasks with their hands at the normal level for controlling the paraglider (in line with the risers, **Fig. 4A**) while 28 (65.1%) kept them at or below the level of the karabiners, in a position that might cause a glider to stall (**Fig. 4B**). For those in SAT, 10 (22.2%) had their hands at riser level, with 35 (78.8%) at or below the karabiners. For the 46 participants able to focus on both of the physical tasks, the majority (25, 54.3%) kept their hands active at the level of the risers. All of the 42 participants who focused on the verbal task, or on neither task, had their hands below riser level. Those in SAT and those who were focused on either the verbal task, or on neither, were more likely to 'lock' their hands at or below the level of the karabiners, close to the stall point (Fig. 4B).

The initial point of contact with the harness for those with underseat reserves ($N = 76$) was dependent on the direction of centrifuge motion. For those in spiral ($N = 35$), 29 (82.9%) began their search for the handle on their hip (**Fig. 4C**) and six on their thigh (17.1%). However, for those in SAT ($N = 41$), 26 (63.4%) attempted to first locate the handle on their thigh (**Fig. 4D**), and 15 on their hip (36.6%). This difference in initial point of contact between spiral and SAT was statistically significant [χ^2 (1 df, $N = 76$) = 14.74, $P = 0.0001$].

Table I. Deployment Times (Seconds) for Successful Deployments ($N = 86$), Broken Down by Phase, from the Deployment Signal to Deployment Bag Release.

	ELAPSED TIME (s)		
DEPLOYMENT PHASE	MIN	MEDIAN (IQR)	MAX
Deployment signal	0	0	0
Control line release	0.28	0.6 (0.46-0.8)	2.34
Handle location	0.5	1.02 (0.78-1.22)	3.98
Handle grip	0.7	1.32 (1.04-1.58)	4.34
Deployment bag out	1.06	1.75 (1.51-2.04)	6.5
Deployment bag release	1.22	2.00 (1.7-2.32)	6.28

Table II. Number (%) of Participants Able to Continue the Tasks Once the Centrifuge Began to Turn.

TASK	SPIRAL (N = 43, %)	SAT (N = 45, %)	OVERALL (N = 88, %)
Physical and Verbal	18 (41.8)	15 (33.3)	33 (37.5)
Verbal only	13 (30.2)	14 (31.1)	27 (30.7)
Physical only	6 (14.0)	7 (15.6)	13 (14.8)
Neither task	6 (14.0)	9 (20.0)	15 (17.0)

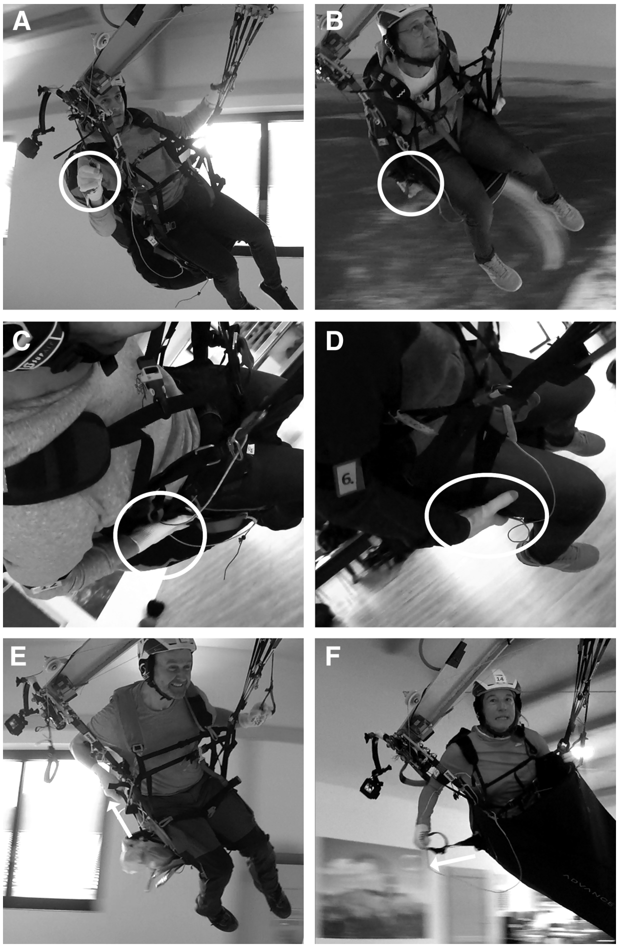

Fig. 4. A.) Participant with hands at the normal 'riser' level. B.) Participant with hands locked below the karabiners, close to the stall point, at the point when the red light illuminated, signaling them to deploy. C.) Participant in spiral first attempts to locate the handle on their hip. D.) Participant in SAT feels first on the thigh. E.) Participant pulls handle directly upwards. F.) Participant pulls the handle directly outwards.

Participants with front-mounted reserves ($N = 11$) touched the handle on the first attempt in 5 (45.5%) cases. However, in four cases, their hands went first to their hip or thigh, as if looking for an underseat reserve. Participants with front-mounted reserves were significantly slower to locate their handle than those with underseat reserves (median 0.5 vs. 0.3 s, $P = 0.034$), but the overall difference in deployment time was not significant (1.56 vs. 1.34, $P = 0.210$).

Those participants who located the handle on first touch had faster median deployment times (1.26 vs. 1.4 s, $N = 87$), but this difference was not statistically significant ($P = 0.153$). In the postrun interview, 74 (84.1%) found locating the reserve handle 'very easy' or 'easy', 7 (8%) 'neither easy nor difficult', and 7 (8.0%) 'difficult'.

Irrespective of whether the deployment bag in underseat systems was designed to be pulled out vertically or laterally, 19 (54.3%) of the 35 spiral and 19 (46.3%) of the 41 SAT participants pulled the handle more vertically ('upwards', defined as less than 45° to the side wall of the harness, **Fig. 4E**) and the remainder more laterally ('outwards') (**Fig. 4F**). There was no significant difference in pull direction between spiral and SAT [χ^2 (1 df, $N = 76$) = 0.21, $P = 0.64$].

Of the 87 participants who attempted deployment (i.e., did not freeze), 86 (98.9%) threw the deployment bag away from the harness in a single sweep once they had extracted it from the container. When asked in the postrun interview whether the deployment felt 'instinctive, not requiring conscious thought', 54 (61.4%) answered 'completely or 'very', 24 (27.3%) 'moderately', and 10 (11.4%) 'slightly' or 'not at all'. There were 71 (80.6%) who found deployment 'very easy' or 'easy', 7 (8%) 'neither easy nor difficult', 7 (8.0%) 'difficult', and 2 (2.2%) 'very difficult'. A total of 59 (67.0%) felt their deployment was 'very effective' or 'effective', 22 (25%) 'neither effective nor ineffective, 6 (6.8%) 'ineffective', and 1 (1.1%) 'very ineffective'.

There were no strong or significant associations between deployment time and participant age, handedness, hours per year, years flying, deployment experience, or self-rated anxiety or disorientation. One participant displayed freezing behavior and failed to take any deployment action at all. Four others showed clear evidence of perseveration. These five participants were also unable to complete both the verbal and physical tasks prior to the signal to deploy. With coaching, they were all able to deploy successfully on subsequent attempts.

The subject matter experts observed that participants appeared generally less stressed than in the previous zipline experiment, perhaps because there was no sudden drop and no time limit for deployment (as opposed to running out of zipline). SAT appeared more challenging to pilots than the spiral, despite lower G forces. There were no qualitative differences in behavior or performance between left and right-handed participants. Participants searched for the handle relative to skeletal landmarks (hip, femur), but rarely looked directly at the handle. Instead, participant gaze was toward direction of travel. Participants had limited head control under G force, especially during SAT and little directional control during the throw. Handles that were prominent, easily felt, and then easily encircled by the hand performed best. Front mounted reserves did not offer advantages over underseat systems, and in some instances appeared to add complexity. They could lift up, if unsecured at the base. Pilots' instincts were occasionally to search for an underseat reserve first, despite having a front-mounted system.

DISCUSSION

Of the participants, 88 threw their reserve parachute while rotating either 'forward' in spiral or 'backward' in SAT configurations on a centrifuge. Participants engaged well with the tasks and, as hoped, found them very challenging. Despite lower G forces, SAT appeared to be the more taxing of the two configurations based on the postrun interviews and subject matter experts' observations (rejecting the first hypothesis). This may be because the sensation was less familiar or because in motion, 'whole body' orientation is derived from perceptions of the visual and force environments. The decoupling of their usual relationship when in flight renders pilots prone to illusions and spatial disorientation.[25] When traveling primarily 'backward' in SAT configuration, the 'optic flow' of the visual world is perceived to be contracting, whereas when moving forward, it is perceived to be expanding.[5,18] Optic flow affects depth perception and postural control, and traveling backward appears to make these more demanding.[5,20]

Participants in SAT, and those particularly challenged by the tasks, were more likely to 'lock' their hands close to the stall position (Fig. 4B) rather than moving them normally at the level of the risers (Fig. 4A). This was felt more likely to be an effort to brace against less familiar sensations, or a reflection of additional cognitive challenges, than a direct effect of the acceleration forces. Indeed, Girgenrath et al. have noted increased isometric force with increasing acceleration (i.e., a tendency to 'overshoot' or 'overcontrol'), which would have implied a greater proprioceptive disturbance in spiral rather than SAT.[10] However, Göbel et al. found this effect ameliorated with practice, so increased familiarity with the sensation of spiral rather than SAT may also have been a factor.[11]

In the postrun interview, more participants in SAT, compared to spiral, commented on the difficulty of the throw (46.7% vs. 18.6%, including lack of power and directional control). This was significant, as reserve deployments in SAT have been notorious for entanglements between the reserve canopy and the main glider. The German Hang Gliding and Paragliding Association once recommended, based on mathematical modeling, that the best way to avoid an entanglement was to throw the reserve hard in the direction of the feet.[21] However, from this study, it would appear unrealistic to expect pilots to have sufficient directional control and power to do so. Throwing toward the feet would also require a compound action (pulling the reserve out and then flinging it forward); all but one participant in the study (98.9%) naturally deployed with a single, backward sweep. This stark difference in deployment action between the zipline study (where some threw with a single sweep and others with compound actions) and the present study might have been due to acceleration forces (again, 'overshooting'), to differences in habits or training, or as a consequence of participants having seen the recommendations from the previous study.[10] However, given that the behavior was so pervasive, it was felt likely that it was an effect of the acceleration.

Based on the previous study, it was hypothesized that the majority of participants with underseat reserves would first attempt to locate the handle on their hip. The hypothesis was accepted for those in spiral (82.9%). However, for those in SAT, the majority first searched on their thigh (63.4%), rejecting this hypothesis. It appeared that the initial search position depended on direction of motion, with a statistically significant difference in first point of contact between spiral and SAT. In spiral and in the zipline study (where 85.1% first searched on the hip), the participants were traveling predominantly 'forward', whereas in SAT they were initially traveling 'backward'. This was corroborated by two participants in the SAT group who first reached for their thigh, but then went on to do an additional centrifuge run in spiral and on those occasions reached first for their hips. One possible explanation is that this was due to the Coriolis effect, in which an object (here, the arm) is deflected within the plane of rotation by the rotation itself. In a clockwise rotation (spiral), the force would act to the left, pushing the hand back. In an anticlockwise rotation (SAT), the force would act to the right, pushing the hand forward.

As with the zipline study, vision appeared to play a lesser role in handle location than touch. Ponzo et al. have commented that sensory information is integrated based on contextual reliability.[19] When something is far away, vision predominates. When it is within reach, location estimation is a product of proprioceptive, tactile, and visual information. Indeed, it was striking how search patterns followed the participants' bony anatomy, first contacting either the hip or the thigh, and then searching along the line of the femur. Some participants, who missed the handle on the first attempt, were observed to go back to the hip to search. Even four of the participants with front-mounted reserves went first to the hip or thigh, despite the handle being visible in front of them.

Some harnesses in the study had been designed so the deployment bag was best extracted by pulling it outwards rather than upwards (Figs. 4E–F). In the zipline study, 70.2% of participants pulled upwards, irrespective of harness design, which proved troublesome for some. It appeared that the upward action better engaged the large muscles of the arm and chest, so it was hypothesized that this would also be the case in rotation. The hypothesis was narrowly accepted, as just over 50% of participants with underseat reserves pulled the handle more vertically than horizontally. In some instances, the outward pull appeared to be an effect of the centrifugal force as much as pilot intention: when pulling up, the arm was flung outwards and backward, away from the harness, or it may have related to the 'overshooting' described above.[10] Even when participants did pull upwards, it appeared to be less of an issue than in linear deployments, perhaps as the deployment bag was also pushed down by the centrifugal force, making it less likely to stick on the top edge of the container. However, corners of the bag appeared more prone to sticking under radial acceleration. As in the zipline study, there were two failures to deploy, one for equipment reasons and one due to freezing. In addition to the participant who froze, there was clear evidence of perseveration in others (accepting the final hypothesis).

The study's main strengths were its large sample of amateur pilots using their own equipment, subjected to realistic forces while undertaking a standardized task that built on previous work. However, as with the zipline before it, the key limitation of the work was its lack of jeopardy. Though the study model was designed to be mentally taxing, pilots were never in danger and were at most anxious, rather than truly frightened. There was little surprise involved, no hesitation that reserve throw was the correct course of action, and no consequences from a slightly slower throw. Though the G onset time was realistic for a collapse becoming an uncontrolled rotation, it was still a gradual rather than sudden challenge.

The use of a standardized grip, gloves, and helmet detracted a little from the study's realism. Given that all the harnesses in the study had their primary reserve parachute handles positioned either in front or on the right side of their harnesses, it would have been desirable to test participants with the handle on the outside and the inside of the rotation. However, this was limited by the design of the centrifuge arm. Equally, SAT could only be tested at a maximum of 3 G, but that limitation also brought an element of ecological validity, as lower acceleration forces are typically experienced in SAT than spiral. Finally, the study participants were chosen by the staff of Flugschule Hochries from a self-selected pool of volunteers. However, all of these limitations meant that participants in the study had an easier task than those in a real emergency. Therefore, the issues highlighted by the study might be considered more pressing given the study's limitations, rather than less.

This study built on our previous work, investigating reserve deployment in a large cohort of amateur paraglider pilots, this time under radial acceleration. The overall rate of failure to extract the deployment bag from the harness was 2.3% (if the 143 participants from both studies were combined, it was 2.7%). This appears far too high for an essential item of safety equipment and improvements are essential. Paraglider pilots are themselves part of the reserve system. Maladaptive behaviors seen in some pilots under stress underlined the importance of the other components working in harmony with pilots' natural responses under pressure, with minimal cognitive demands and with no need for innovation or problem-solving. Based on the previous study and the work described in this paper, our final recommendations to improve paraglider reserve parachute system design and training are as follows:

1. Reserve handles should be positioned on the hip for underseat systems.

   The majority of pilots in both studies searched for the reserve handle on their hip. Despite some participants searching on their thighs during SAT, this is outweighed by the frequency of forward rotation during emergencies and the overarching benefits of standardization. The hip is also less likely to shift significantly relative to the harness (compared to the thigh position) during instability.
2. Handles should be prominent, tactile, brightly colored, easily encircled by the grip, and positioned clear of other harness components.

   Participants rarely looked for their reserve and relied on touch instead. So, in standardizing the handle, particular efforts should be made to make the handles prominent and tactile, especially for pilots using thick gloves. If the handle were made too prominent then there would be an increased risk of accidental deployment, but a balance should be struck that allows the handles to be easily located and encircled. Since looking was used as a rescue strategy when participants could not find the handle by touch alone, they should remain brightly colored.
3. Deployment bags should be supplied with the harness, strop, and handle as part of an integrated system, including an indication of correct orientation during installation.

   Integrated systems, with deployment bags supplied by the harness manufacturer rather than the reserve manufacturer, appeared to function more successfully in both studies. If the components are still supplied separately, then care should be taken to ensure the strop is of the correct length for the pilot. A correctly sized strop is one long enough to avoid pulling or rotating the deployment bag before the pins are released, but short enough that the deployment bag can be pulled well clear of the harness before the pilot's elbow and arm are fully extended.
4. The deployment bag should be extractable at any angle of pull.

   Though the effects of pulling upwards instead of outwards were less of a concern during radial acceleration than linear, they remained significant. Harnesses should be designed so bags are extractable at any angle of pull.
5. Front mounted reserve containers should be secured at the base to prevent them lifting when pulling the reserve handle.
6. Pilots need to be considered a part of the reserve system and need to increase their reserve deployment drills by an order of magnitude. They should be encouraged to do so as part of a 'post-takeoff check', as well as multiple times during the flight.

   A formal post-takeoff check that included encircling (not just tapping) the reserve handle once flying on a safe course should become part of training and practice. More time during basic training should be devoted to familiarizing students with their reserve parachute system. Paragliding students should understand reserve fitting, bridle routing, and the importance of periodically loosening hook-and-loop fasteners. Before finishing their course, students should sit in a harness suspended from a hang point and practice throwing multiple times with a dummy reserve to understand the angles and forces required. Ideally, qualified pilots would also undertake similar practices when buying a new harness or reserve parachute.
7. Deployment in a single sweeping action should be encouraged in preference to compound actions or complicated instructions to throw in particular directions in different situations to avoid entanglement.

Few participants appeared to have sufficient directional control, let alone cognitive bandwidth, to direct their parachute once extracted from the harness. The message to 'just deploy' cannot be emphasized enough.

This evidence-based simplification and standardization would represent a step forward in design and instruction that has the potential to save lives and prevent serious injury. Above all, pilots should be encouraged to throw their reserve promptly in an emergency.

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Authors and Affiliations: Matt Wilkes, Ph.D., Geoff Long, M.Phil., Heather Massey, Ph.D., Clare Eglin, Ph.D., and Michael J. Tipton, Ph.D., University of Portsmouth, Portsmouth, Hampshire, United Kingdom; and Rebecca Charles, Ph.D., Rail Accident Investigation Branch, Derby, Derbyshire, United Kingdom.

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