



Ergonomics of paragliding reserve parachute deployment in linear acceleration

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1. Introduction

Paragliding is a widely-practiced form of unpowered flight, with an estimated 127,000 active paraglider pilots worldwide [16]. While paragliding has become safer over time, it remains a relatively high-risk pursuit: of the 22,345 registered pilots paragliding in France in 2015, there were 15 deaths (0.06%) and 515 reported injuries (2.3%) [15]. While the vast majority of manufacturers build their equipment to meet European Norm (EN) standards [5]; [6] [7] equipment remains variable in its design and quality. Concerted, systematic efforts to improve equipment and training are imperative for the evolution of the sport and the safety of its practitioners.

Paragliding equipment consists of a main canopy (a 'wing'), a harness and a reserve parachute. Reserve parachute deployments are rare in recreational paragliding as, when the wing enters an unflyable configuration, the pilot first attempts recovery manoeuvres to restore it to normal flight. Recovery is generally preferable to reserve deployment, as it allows the pilot to continue flying and to avoid the hazards of an unsteerable descent under parachute. However, if the recovery manoeuvres are unsuccessful, the pilot must ensure sufficient time remains to deploy the reserve parachute before impacting the ground. Accident investigations have often commented on the failure of paraglider pilots to deploy their reserve parachutes in time [19]. In an analysis of incident reports from 2017, the Fédération Française de Vol Libre (FFVL) concluded that in 90% of accidents, the reserve parachute was not deployed [19]; [10], consequently those accidents led to nine deaths

[9].

The components of a reserve parachute system are the reserve handle (held in place by hook and loop fastener), a strop (connecting the handle to the deployment bag), a deployment bag (holding the reserve parachute), and the reserve parachute itself (Fig. 1). The deployment bag sits within a 'container' in the harness, kept closed by pins attached to the reserve handle. The container can be mounted in front ('front-mounted system') or underneath the pilot ('under-seat system'). For under-seat systems, the handle is mounted on the right of the harness. The only exceptions are some competition and acrobatic harnesses with two reserve parachutes, where the primary reserve is on the right and a secondary reserve is on the left.

Therefore, at a minimum, deploying the reserve parachute requires the following eight steps: [1] remove hands from the control lines; [2] locate the reserve handle; [3] grip the reserve handle; [4] loosen the reserve handle hook-and-loop fastening; [5] pull the handle away from the harness, releasing the pins that open the container and tensioning the strop; [6] Extract the deployment bag from the container in the harness; [7] Throw the deployment bag away from the harness; [8] Release the grip on the reserve handle. The reserve parachute lines then come under tension, pulling the parachute from the deployment bag, exposing it to the airflow and allowing it to open. The pilot then swings under the reserve parachute, suspended by the reserve bridle connected to attachment points (usually at the shoulders).

This mechanical process is part of a longer 'chain of survival', that begins with the decision to deploy the reserve, and finishes by disabling

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the main wing in preparation for landing under the reserve canopy. The minimum altitude required for successful deployment will depend on a number of factors, including descent rate and reserve size. However, as the 2017 FFVL report indicated, making the decision to throw the reserve is the critical step [10]. The decision requires complex cognition, including task switching and situational awareness, under high levels of stress.

However, stress in the aviation context can narrow attention, reduce visual scan, leads to reductive and limited thinking, regression, hurried decision making and decrements in working memory capacity and retrieval [14]. In other situations of significant stress, such as helicopter underwater escape training (HUET), working memory and cognitive function have been shown to be impaired [18]. It is consequently of paramount importance that the reserve parachute system works efficiently and instinctively, as 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. Indeed, 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 [12],[13], Leach, 2004 During a paragliding emergency, 10 s can equate to hundreds of meters of lost altitude and, in a spiral, acceleration forces sufficient to induce loss of consciousness [21].

Training of reserve parachute deployment in paragliding is inconsistent: pilots are instructed on the correct procedures during initial training, some will then practice the deployment movements during solo flights, while a much smaller subset will actually deploy their reserve parachutes as part of a training course or genuine emergency. Pilots are also taught differing techniques for deployment [2]. These 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 forwards

then throwing it backwards.

Finally, parachute deployment systems vary significantly in design, and each element may be made by multiple, separate manufacturers. While new designs are trialled by professional test pilots before commercial release, such pilots are not typical of the flying population: test pilots fly many more hours and deploy reserve parachutes frequently as part of their work. Intuitive design, guided by participatory studies, may increase the success rates for non-expert pilots.

In skydiving, two authors [4]; [1] have studied jumpers operating their deployment handles ('ripcords') and riser releases, finding that not all could generate the forces required to deploy their parachutes. Building on their work, [11], subsequently investigated the optimum position for the deployment handle, finding some positions superior with regard to pull forces and others for visibility, with the thigh as the best compromise. Their work lacked ecological validity as the participants were suspended vertically (in skydiving, deployment is typically from a horizontal 'belly down' position). Skydiving deployments are very different to paragliding reserve deployments, as they occur at terminal velocity, in a much more constrained harness, and the deployment is an intrinsic part of every jump rather than a rare event. Nonetheless, their work provided a foundation for this study. A similar approach was demonstrated in HUET, where lack of consistency in the position and opening mechanisms of escape hatches reduced the chances of successful escape [3]. Some systems were shown to be ergonomically superior to others given participants' instinctive responses under stress [3]. Developing reserve parachute systems that are coherent and that work in harmony with pilots' natural responses may therefore save time, altitude and ultimately lives.

To this end, we filmed 55 reserve deployments by amateur paraglider pilots. The deployments took place whilst descending a zipline designed

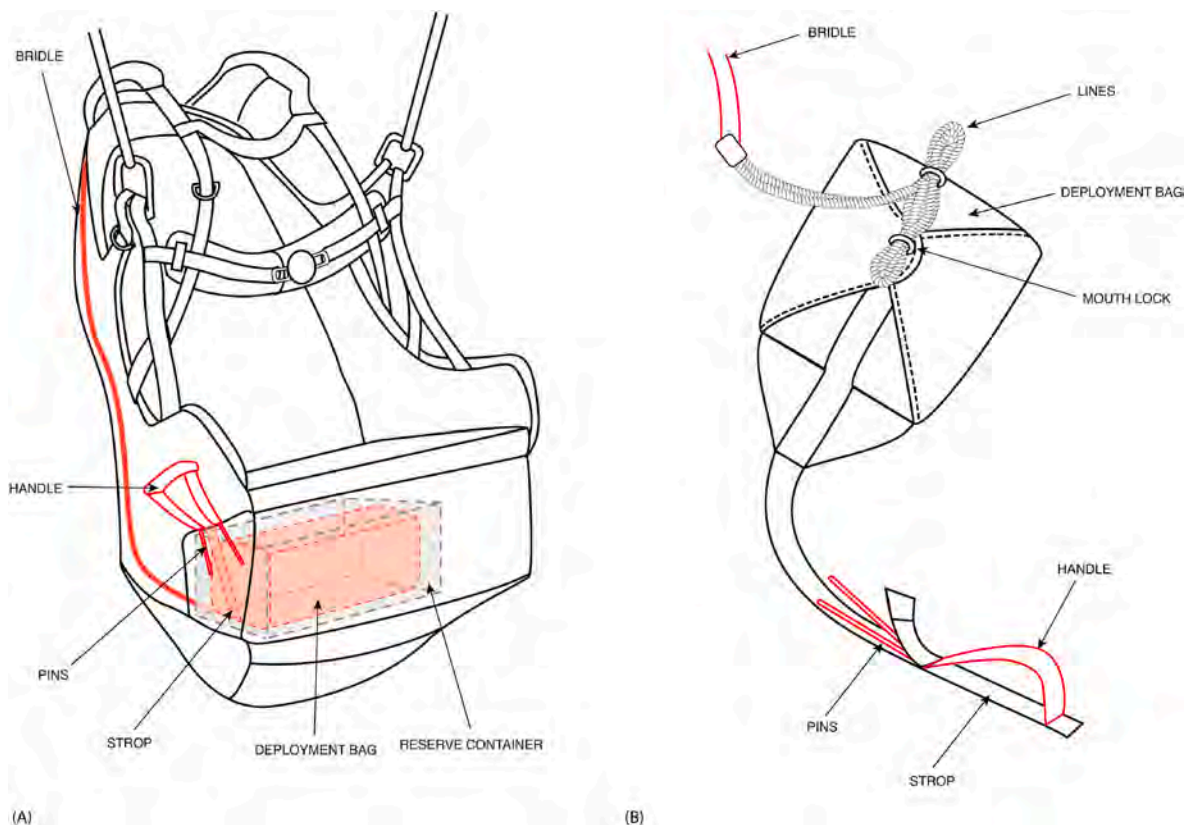


Fig. 1. Under-seat reserve parachute system. (A) The deployment bag, containing the reserve parachute, sits within the reserve container of the harness. When the handle is pulled, the pins are removed, allowing the reserve container to open and the deployment bag to be extracted. Once the parachute inflates, the pilot hangs underneath it connected by the reserve bridle. (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.

to mimic the body position, as well as the cognitive load of a real deployment. The footage was reviewed and discussed by two expert focus groups including pilots and instructors. We hypothesised that participants with previous deployment experience or front-mounted reserve systems would have faster, more successful deployments. However, the broader aim was to characterise pilots' instinctive responses, while exploring whether there were human or design factors that might influence the chances of a successful deployment.

2. Materials and methods

This study centred on an annual event called the “Big Fat Repack”, organised by Thames Valley Hang gliding and Paragliding Club. The event gave pilots the opportunity to practice throwing their reserve parachute from a zipline, before having it professionally repacked. Their zipline descents were filmed by two cameras attached to the zipline trolley: a GoPro Hero 7 (front view) and a GoPro Hero 5 (side view), both set to 2.7 k, 50 fps and linear field of view (GoPro Inc., San Matteo, USA).

2.1. Ethical approval

The study was approved by the University of Portsmouth Science Faculty Research Ethics Committee [SFEC 2018–133]. All participants provided informed, written consent and the study complied with the Declaration of Helsinki.

2.2. Participants

Fifty-five practicing paraglider pilots volunteered to take part in the study (mean [SD] age 49.2 [12.5] years). Three (5.4%) were female and 52 (94.6%) male. Nine (16.3%) were left-handed and 46 (83.7%) were right-handed. Twenty-seven (49.1%) had been flying for three or fewer years. Thirty-six (65.5%) flew less than 25 h per year, 14 (25.5%) flew 26–50 h per year and 5 (9.0%) more than 51 h per year. Twenty-eight (50.9%) described their flying currency as ‘very low’ or ‘low’, 23 (41.8%) as ‘average’ and 4 (7.3%) as ‘high’ or ‘very high’. Thirty participants (54.5%) had some experience of reserve parachute deployment, defined as having thrown their reserve at a previous indoor event, during a training course or in a real emergency. Twenty-five (45.5%) had no such experience.

2.3. Paragliding equipment

All participants used their own paragliding harness, reserve parachute system and helmet. Participants were issued with standardised, appropriately-sized gloves (Dura Gloves Etouch, DeFeet International, Hildebran, USA) and held the control handles in an open ‘beginner’ grip, to eliminate glove-thickness and control handle entanglement as confounding factors.

2.4. Study process

2.4.1. Initial questionnaire

Participants filled out an initial questionnaire, which included demographic and equipment details, flying experience, reserve deployment experience, repacking practices and self-rated flying currency.

2.4.2. Practice station

All participants attended a practice station, to ensure that all had the same baseline level of information and currency regarding reserve parachute deployment. They were given standard instructions that as soon as they felt themselves released down the zipline, they should “[1] Rapidly locate the deployment handle [2] Extract the bag [3] Throw the reserve hard away from the paraglider [4] Release the deployment handle.” These instructions were derived from the manuals supplied

with two typical, commercially-available, reserve parachutes (Ozone Angel, Ozone Gliders Ltd, Edinburgh, Scotland; Supair Fluid, Supair VLD, Annecy, France). Participants then sat in their harnesses, practiced the zipline tasks for 1 min (detailed in 2.4.4) and located their reserve handle. When gripping the reserve handle, they were measured for acromion-olecranon and olecranon-wrist crease lengths and angles of flexion at the shoulder and elbow [17]. The same observer made all measures using a 12-inch goniometer (66 fit Ltd., Spalding, U.K.) and a new fibreglass measuring tape (HaB International Ltd., Southam, U.K.).

2.4.3. Zipline

The zipline was indoors and approximately 50 m in length. Participants ascended to the zipline platform by stairs. They were given 5 min to settle following the climb and then lowered over the side in their harness and held suspended by a tether.

Once over the side, participants were held at an awkward angle (Fig. 2) approximately 15 m above the floor, which heightened anxiety and ensured that, when released, they would experience drop, pitch and yaw akin to their wing collapsing in flight. Their hands were in dummy control lines, positioned and weighted to feel like those of a typical commercial paraglider (Ozone Swift 4, Ozone Gliders Ltd., Edinburgh, U.K.).

2.4.4. Task

The aim of the zipline task was 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. To this end, they were asked to look up at two LED lights and, when one switched on, to apply input to the control line on the corresponding side. At the same time, they were given a form of the Verbal Fluency Task [20] which engaged executive function and working memory. The task required participants to name as many different words as they could beginning with the letter ‘A’, not including people or places or the same words with different endings. They were then released down the line, without warning, 15–60 s after beginning the zipline tasks.

Thus, at the point of release, participants had their hands in the control lines in their usual flying position, their gaze was directed upwards (towards their ‘collapsed wing’) and they were experiencing high levels of cognitive load in multiple domains. They then had to make a task switch from ‘fixing their wing’ to deploying their reserve parachute as soon as they felt movement down the zipline (Fig. 2).

2.4.5. Post-questionnaire

Immediately after their zipline run, participants were asked to rate their deployment experience in four domains (engagement with the task, and their feelings of instinctiveness, ease and effectiveness of the deployment) on a five-point categorical scale (“Not at all”, “Slightly”, “Moderately”, “Very”, “Completely”).

2.5. Data analyses

2.5.1. Video analysis and focus groups

The video footage was edited, analysed and reviewed in Objectus Studio (V 1.0.2, Objectus Technology LLC, Philadelphia, USA). Footage from all participants was shown to two expert focus groups. The first (Flyeo Paragliding School, Doussard, France; April 4, 2019) consisted of three senior paragliding instructors, who specialised in training pilots in the management of in-flight emergencies. The second (Cranfield University, UK; April 26, 2019) included the British Hang gliding and Paragliding Association (BHPA) Chief Technical Officer; the BHPA Emergency Parachutes' Advisor and Senior Parachute Repacker; a Flight Test Engineer from Airbus Ltd. and a lecturer in Human Factors from Cranfield University. The discussion from the focus groups was recorded, then subsequently transcribed and reviewed using TRINT software (TRINT Ltd., London, UK), coded thematically and summarised for



Fig. 2. Zipline set up in the moments before release for a participant with a front-mounted system. (A) Cameras; (B) LED lights; (C) Hands in control lines responding to the light sequence; (D) Gaze directed upwards; (E) Tensioned release.

presentation.

2.5.2. Quantitative and statistical analysis

Analysis was conducted using R Studio (Version 1.0.143, R Core Development Team, version 3.4.1).

The different harness and reserve parachute combinations were assigned to four categories for grouped comparisons: 'seated harness, under-seat reserve' (37, 67.2%), 'seated harness, front-mounted reserve' (7, 12.7%), 'cocoon harness, under-seat reserve' (10, 18.1%), 'cocoon harness, front-mounted reserve' (1, 1.8%). For comparison of deployment speeds, the primary metric was elapsed time from control line release, rather than from the start of zipline descent. This meant that the reaction time component (the time taken to realise that the descent had started, and it was time to deploy) would not affect the results. Distribution of the 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, non-parametric tests (Wilcoxon Rank Sum and Spearman's Rank Correlation) were used instead. Multiple comparisons were corrected using the Holm-Bonferroni method. Significance was set at $p \leq 0.05$ and data presented as mean (SD) unless otherwise stated.

3. Results

3.1. Practice station

Of the 47 participants with under-seat reserves, 33 (70.2%) were able to reach their reserve handle with both hands, while suspended in the harness during the practice station. Eight (17.0%) could do so with difficulty, and six (12.8%) could reach it with one hand only.

3.2. Zipline deployments

3.2.1. Deployment rates and times

Fifty-three of the 55 participants were able to successfully deploy their reserve parachute before reaching the end of the zipline. Of the two that failed, one had an improperly packed parachute, while the other grabbed the leg stirrup in addition to the reserve handle, which prevented him from extracting the deployment bag from the container. Though the solution was straightforward (release the stirrup, or grab the bag itself), the participant appeared cognitively overwhelmed by the failure and was unable to solve the problem in the remaining 7.1 s of his zipline run (see Fig. 5B in the Discussion, below). Deployment times were moderately right-skewed. For successful deployments, the median time from the deployment signal to releasing the deployment bag at the end of the throw was 2.46 (IQR 2.15–2.97) seconds, with a minimum time of 1.44 s and a maximum time of 5.12 s. The median time from control line release to releasing the deployment bag was 1.66 (IQR 1.37–2.18) seconds, with a minimum time of 0.84 s and a maximum time of 3.72 s.

3.2.2. Handle location

Forty-six (83.6%) participants turned their heads towards the reserve side but only 14 (25.4%) followed the deployment bags' course once thrown. For participants with under-seat reserves ($n = 47$), 40 (85.1%) first attempted to locate the reserve handle on their hip and 7 (14.9%) on their lateral thigh (irrespective of the handle's actual position). Consequently, only 15 (31.9%) of these participants touched the handle on the first attempt, the majority searched either behind (21, 44.7%), above (6, 12.7%), forward (3, 6.4%) or below (2, 4.3%) the handle's true position. In contrast, all participants with front-mounted systems located the handle on the first attempt. Those participants who located the handle on the first attempt had significantly faster deployment times (median

1.5 vs. 1.84 s, $p = 0.007$, $n = 53$) than those who did not.

3.2.3. Deployment bag extraction

Irrespective of whether the deployment bag in under-seat systems was designed to be pulled out laterally or vertically, 33 (70.2%) of participants' initial movements was an upwards or upwards-backwards pull, effected by shoulder abduction (19, 57.6%), extension (6, 18.2%) elevation (4, 12.1%) in combination with elbow flexion (Fig. 3).

3.2.4. Throwing action

Twenty-eight (60.9%) participants with under-seat reserves threw the deployment bag away from the harness in a single sweep, once they had extracted it from the container. The remaining 39.1% attempted to bring the bag upwards and forwards before throwing it back (a 'compound' action, taught by some schools). The participants who threw with a single, sweeping action had significantly faster deployments than those who employed compound actions (median 1.56 vs. 2.33 s, $p = 0.003$, $n = 46$, Fig. 4). However, there was no significant difference for those with front-mounted systems.

3.2.5. Participant factors

There were no significant correlations between deployment time and participant age, self-rated anxiety or currency, deployment experience, flying experience, arm length or angles of flexion when holding the deployment handle (Table 1).

There were no significant differences in deployment times between female and male ($p = 0.668$) participants. Nor were their differences between left- and right-handed participants in locating the handle ($p = 0.691$) or deployment time ($p = 0.958$).

3.3. Post-questionnaire

Fifty-one of the 55 participants filled out a questionnaire immediately after descending the zipline. The other four elected instead to repack their reserves straightaway. Twenty-five (49.0%) stated that they felt either "very anxious" or "mildly anxious" prior to descent. Forty-

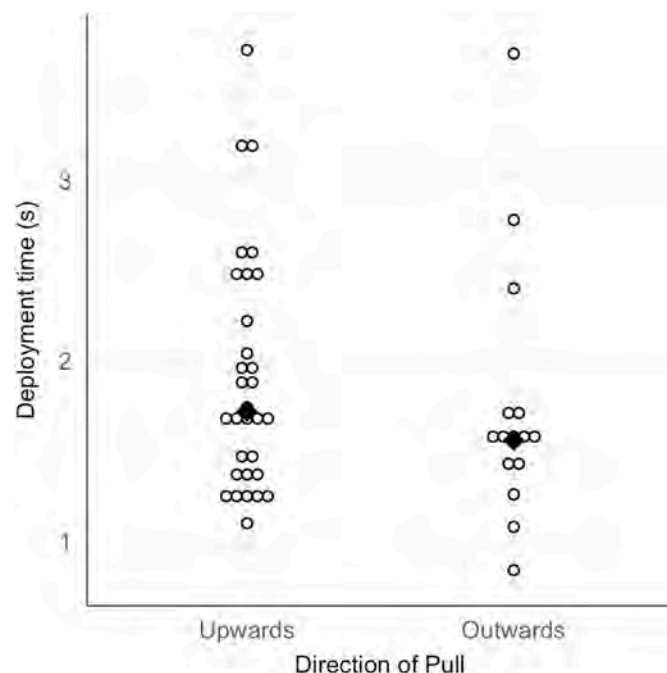


Fig. 3. Dot plot of deployment time against pull direction. More participants pulled upwards than outwards, irrespective of the harness manufacturer's stipulations (individual dots represent a single deployment, diamonds the median deployment time).

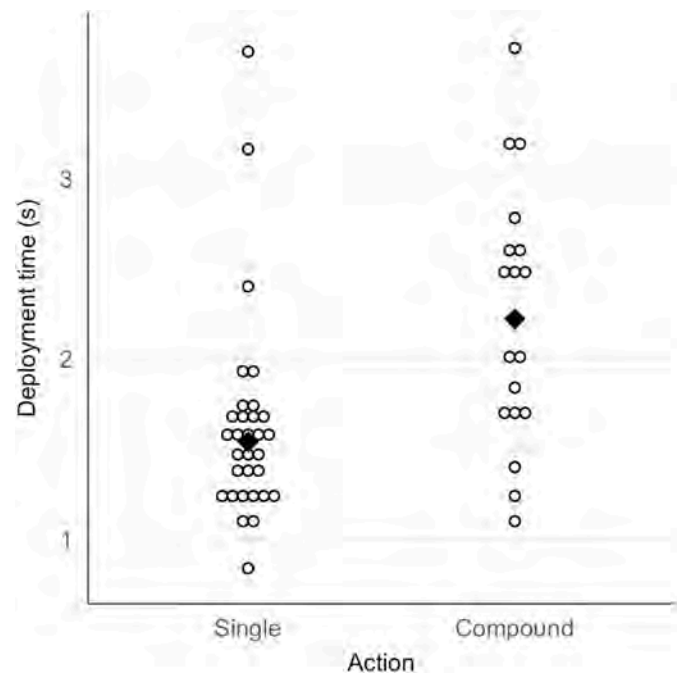


Fig. 4. Dot plot of deployment time against throwing action. Single actions were significantly faster than compound actions ($p = 0.003$). (Individual dots represent a single deployment, diamonds the median deployment time.)

three (82.7%) stated they were "completely" or "very" concentrated on the lights, control lines and verbal fluency test before the zipline released.

When asked if the deployment felt "instinctive, not requiring conscious thought", 15 (29.4%) answered "not at all" or "slightly", 15 (29.4%) answered "moderately", and 21 (41%) answered "very" or "completely". Forty-four (86.2%) found locating the reserve handle "easy" or "very easy". Thirty-six (70.6%) found deploying the reserve was "easy" or "very easy" and 40 (78.4%) felt their deployment was "effective" or "very effective".

3.4. Focus group observations

Both focus groups identified similar themes arising from the video footage. Their narrative observations have been summarised below, and ordered into the sequence of a reserve deployment, beginning with pilot behaviour, and then focussing on individual components of the reserve parachute system.

3.4.1. Body position during deployment

- Participants braced themselves, or made oppositional movements, with legs or arms when first released from the tether, and when deploying (Fig. 5). Most gripped the non-reserve side riser, with their hands either in or out of the control handle.
- Bracing using the opposite riser (Fig. 5A) or pulling the handle with a lot of force could twist the harness and potentially affect the process of deployment.
- Long drops exacerbated these movements.
- Participants tended to curve their body away from the reserve side of the harness, even though their best reach and mechanical advantage would have been to lean over the reserve side.

3.4.2. Locating and gripping the reserve handle

- Participants search for side-mounted handles began at the hip. They would typically slap the area of the harness adjacent to their iliac

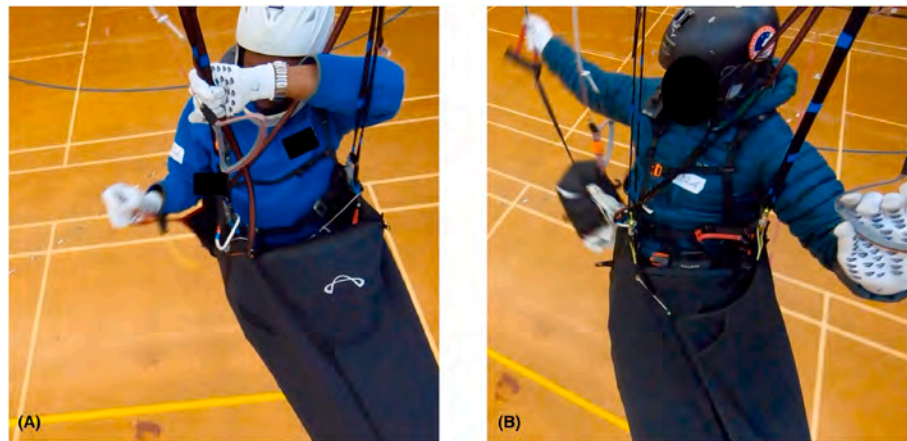


Fig. 5. (A) Participant braces themselves by gripping the opposite riser. (B) Participant makes an oppositional movement with their left hand. Both participants curve their torso away from the reserve side.

Table 1

Correlations between the deployment time (time between releasing the control lines and releasing the deployment bag) and participant measures.

Measure	n	R_s	R^2	p
Age	50	0.164	0.027	0.255
Anxiety	50	0.089	0.008	0.540
Currency	50	0.083	0.007	0.567
Flying experience	50	-0.099	0.010	0.492
Deployment Experience	50	0.013	<0.001	0.928
Arm length	50	-0.177	0.031	0.224
Elbow flexion	50	0.105	0.011	0.474
Shoulder flexion	50	-0.048	0.002	0.744

crest with an open palm (Fig. 6A). If the handle was not positioned there, then they would typically search distally along the axis of the femur.

- Front mounted reserve handles appeared to be easily located in all cases.
- When participants turned their heads towards their reserve, they did not appear to be looking for the handle specifically. They only made a concerted effort to look for the handle if they had encountered a problem. Their primary focus appeared to be their trajectory down the zipline.
- Other accessories, including stirrups, speed bars and participants' clothing had the potential to confuse participants during handle location (Fig. 6B).



Fig. 6. (A) Participant's first attempt to locate the reserve handle is on his hip, despite that being significantly behind the handle's actual position. (B) Participant grabs his reserve handle, and his harness stirrup at the same time, is unable to the extract the deployment bag and fails to deploy.

- Participants would only throw their reserve once they had closed their grip around the handle, with the thumb through the handle loop.

3.4.3. Deployment bag extraction

- The majority of participants pulled the reserve handle upwards (Fig. 7A), even if their equipment mandated a lateral pull. They continued to pull upwards, even when the deployment bag was stuck. The increased resistance made participants pull harder and they would preferentially change their grip to increase the force of upward pull before changing the direction of force (Fig. 7B).

3.4.4. Single vs. compound throw for under-seat containers

- A single, sweeping, backwards throw appeared to be the cleanest, quickest and most effective way to deploy the reserve from an under-seat container (Fig. 8A).
- Compound movements (Fig. 8B) appeared more hazardous, with a higher chance of entanglement with the bridle or reserve lines (Fig. 8C).
- It was unclear whether single or compound movements had more power. However, because of the inertia of the deployment bag, compound movements seemed subject to 'lag' and a loss of power when the strop lost tension. Some participants appeared to throw powerfully and with intention, others let the bag drop.

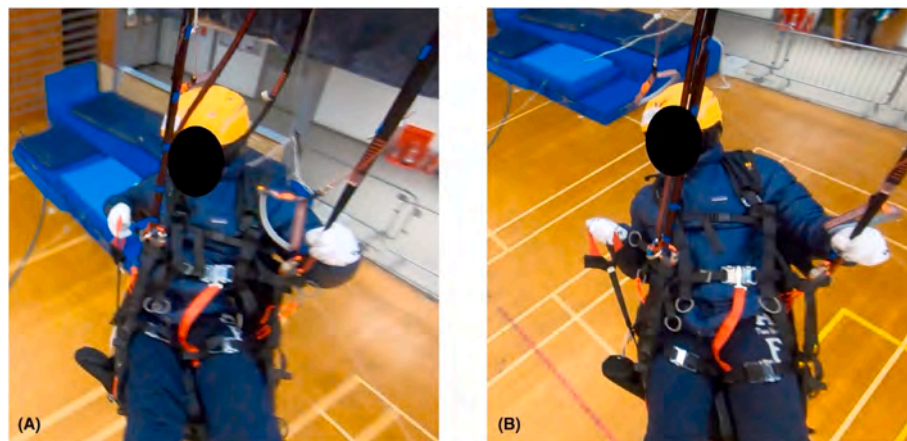


Fig. 7. (A) Participant attempts to extract deployment bag using an upwards pull, causing the bag to stick. (B) Rather than adjust the angle of pull more laterally, the participant changes their grip so they can pull upwards with more force.

3.4.5. Deployment bags and containers

- Deployment bags often appeared to have been installed upside down, which in some instances appeared to slow extraction (Fig. 9A).
- Deployment bags designed to fit the harness appeared to work more cleanly than bags supplied with the reserve parachute.
- Heavily enmeshed hook and loop fastener was a concern during all stages of deployment (Fig. 9B).

3.4.6. Strop length

- Correct strop length was crucial in small participants or those with shorter arms.
- Overly long strops could significantly impede pulling bag from the container and/or reduce mechanical advantage (Fig. 10A).
- Deployment bags had their own inertia when dangling from the strop. Shorter strops helped keep the system under tension and reduce risk of entanglement.
- Short strops that attached at the edge and in the centre of the bag helped the participant release the bag from the container, by converting upward to outward movement (Fig. 10B).

3.4.7. Points specific to front-mounted systems

- Front mounted systems appeared to be easily reached with both hands (Fig. 11A).
- Handles were always in clear view of the participant.
- Handle angles/positions that facilitated a sweeping, outward movement appeared to be most effective.
- When the base of reserve container was not secured, the container moved upwards, making the reserve hard to deploy or reducing mechanical advantage during deployment (Fig. 11B).

4. Discussion

Reserve parachute deployment is a relatively rare event in paragliding. As a result, it is infrequently practiced by pilots and the design of the deployment system is often secondary to other considerations, such as aerodynamics, comfort or equipment weight. However, when deployments do occur, pilots may be low to the ground, disorientated and under tremendous stress [19]. Failure to deploy cleanly can result in death or severe injury. It is therefore essential that the equipment works in harmony with pilots' natural responses under pressure, with minimal cognitive demands and, in particular, with no requirement for innovation or problem-solving.

Fifty-five amateur pilots were observed deploying their reserve

parachutes from a zipline. While the study could not replicate the stress of a real emergency, strenuous efforts were made to make it as ecologically valid as possible. These included tasks that ensured participants' body, hands and gaze were in realistic positions, and an element of surprise and some physical disorientation at the point of release. The zipline task was designed to engage the cognitive systems that we felt most important during a reserve deployment (visuospatial, motor, working memory and executive function) in an overwhelming fashion, with the participants being forced to make a cognitive switch from one task ('fixing the wing') to another ('deploying the reserve').

Rather than vastly experienced test pilots, 91% of the participants in this study flew less than 50 h per year. The majority used underseat reserve systems. While this study demonstrated some of the advantages of front-mounted systems, notably handle visibility, disadvantages include more complex bridle routing, connection before every flight, difficult integration with reversible harnesses and restriction of pilot view. As a result, front-mounted systems are less popular, and they did not lead to significantly quicker deployment times in this study (so, rejecting the hypothesis that front-mounted systems would be faster).

The necessity of the study was highlighted by the high proportions of participants who did not find their deployments instinctive, easy or effective. Indeed, two failed to deploy altogether, with potentially fatal consequences in a real emergency. For an essential piece of safety equipment, these imply significant room for improvement, both in terms of pilot training and equipment design.

4.1. Handle location

Traditional teaching on reserve parachute deployment is to look for the deployment handle, extract the deployment bag, bring it forwards and then throw it hard outwards towards clear air, following its course to check it has opened correctly [2]. However, while the majority of participants turned their heads towards the reserve side, most did not appear to fix the handle with their gaze. Instead they seemed more focussed on their own trajectory down the zipline. Only a minority followed the deployment bags' course. From video analyses, those who looked more fully at the reserve handle appeared more likely to follow it once thrown. Therefore, the rationale for teaching people to look at the reserve handle might be so that they give the whole process their full attention, rather than simply to aid handle location. However, brightly-coloured handles, lead lines or arrows pointing to the reserve handle might still be useful visual stimuli, both for handle location and as a visual reminder to task switch from fixing the wing to initiating deployment.

Participants appeared to locate their handle more by touch than by sight. Locating the handle on the first attempt saved an average of half a

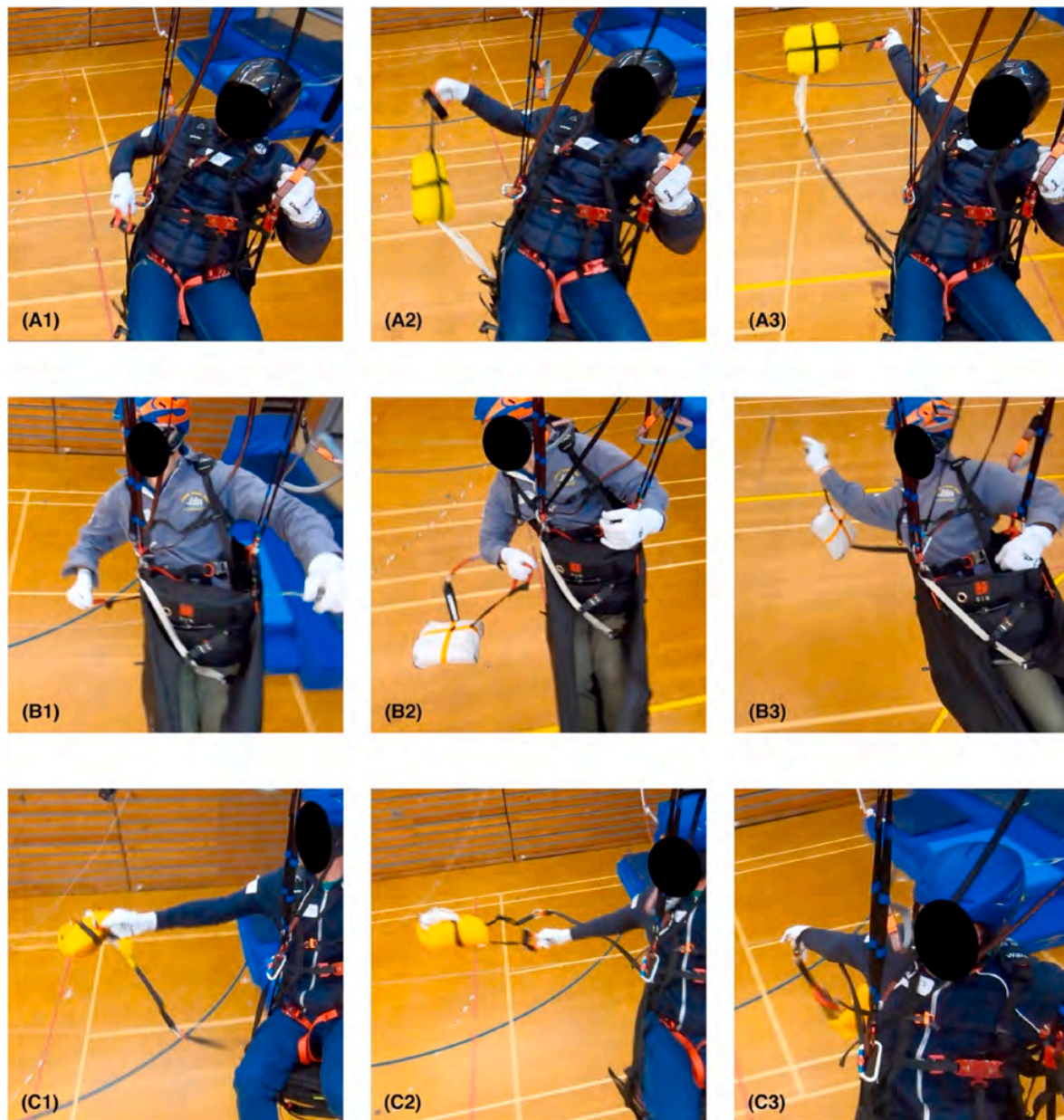


Fig. 8. (A) Participant throws in a single backwards sweep (single action). (B1) Participant extracts the bag; (B2) Brings it forwards; (B3) Throws it back (compound action). (C1) Participant brings the bag forwards; (C2) Inertia means the bag is still moving forwards when his hand starts to travel backwards to throw; (C3) This allows the reserve bridle to form a loop around his wrist.

second, underlining the importance of handle position and design. It was notable that the majority (85%) of participants with under-seat systems first felt for the reserve handle on their hip (irrespective of the handle's actual position), and then along the line of the femur, which may have indicated a natural tactile or proprioceptive response corresponding to the appendicular skeleton (Fig. 6A). Moving the handle to the area of the harness overlying the ilium would very likely increase success. It would also move it clear of other components of the harness, such as the stirrup or speed bar, grasped in error by some participants. Pilots might also be particularly vulnerable when switching between harnesses with handles in different positions: a further argument for standardisation.

The focus group observed that none of the participants pulled the handle until they had completely encircled it with their grip. Therefore, small handles, flush with the harness, might delay deployment (as well as location, especially if wearing thick gloves). However, handles that are too large or prominent may increase the chance of an accidental

deployment.

4.2. Deployment bag extraction

The shape of some under-seat deployment containers demands that pilots pull the deployment bag laterally away from the harness. However, 70% of participants' initial movements was an upwards or upwards-backwards pull, even if the harness design demanded otherwise (Fig. 7A). This caused resistance to bag extraction, but participants were observed to adjust their grip to pull upwards even harder when they felt resistance, rather than change their angle of pull (Fig. 7B). This apparent tendency to pull upwards, rather than outwards, may have been due to participants' desire to extract their reserve parachute with strength and urgency. Pulling upwards predominantly engaged the biceps and large muscles of the chest and upper back, while keeping the arms close to the body. To extract it laterally required participants to

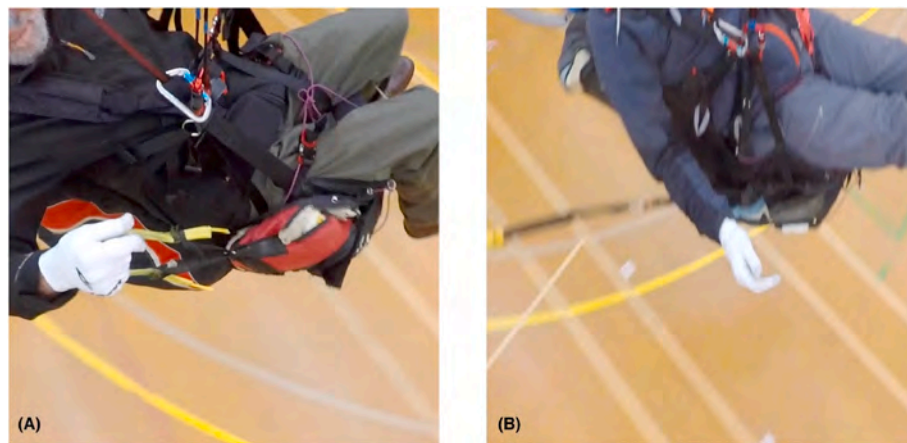


Fig. 9. (A) Reserve is installed upside down, and the lines catch on the top of the container. (B) The enmeshed hook and loop fastener slows the bridle in tracking up to the shoulders, despite being under tension from the parachute.

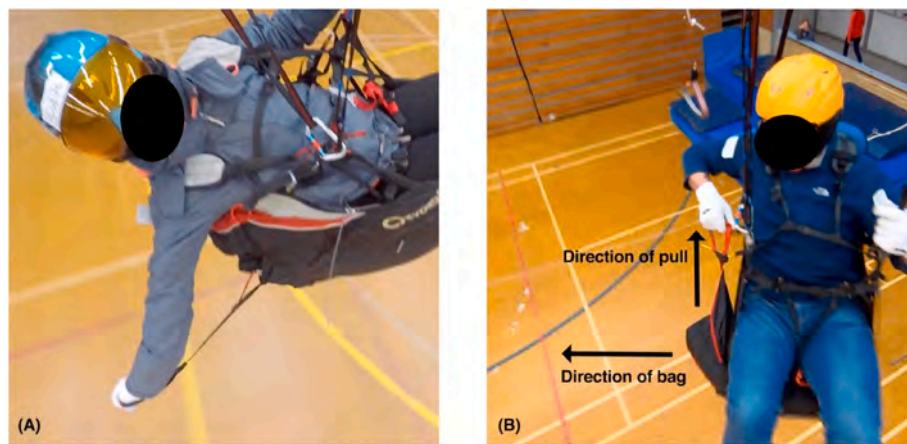


Fig. 10. (A) Participant is at maximum extension, but the excessively long strop means the deployment bag is still in the container. (B) The short strop, attached to the centre and edge of the deployment bag, facilitates its extraction despite an upward pull.

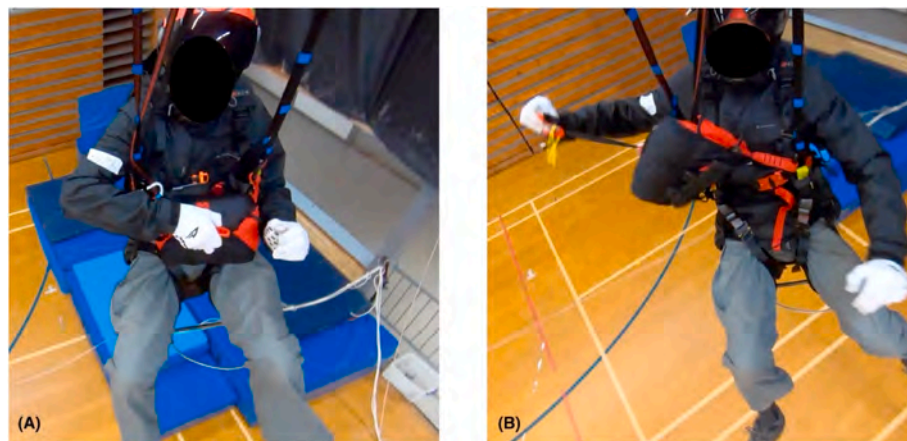


Fig. 11. (A) The participant easily grasps the reserve handle of his front-mounted system. (B) As it was unsecured at the base, the container lifts up before the deployment bag is extracted, increasing difficulty of extraction and reducing the mechanical advantage of the subsequent throw.

abduct and rotate at the shoulder and then pull the bag out using the triceps and lateral deltoid from a relatively weak (and vulnerable) point in the shoulder's arc. This weaker movement may have felt less instinctive to participants under the stress of deployment, even though it was what the equipment demanded of them.

Difficulty in extracting the deployment bags was also increased by strops that were too long for the pilot (Fig. 10A), while short strops positioned to convert upward to outward movement appeared to facilitate extraction (Fig. 10B). It is therefore essential that future designs accommodate all angles of pull, including directly upwards, rather than

relying on pilots to remember to extract the deployment bag in a particular direction during an emergency.

While those with front-mounted systems generally extracted the deployment bags with relative ease, it was notable that if the front-mounted container was unsecured at base, it could lift up with the handle pull, increasing difficulty and reducing mechanical advantage (Fig. 11B). This would be a very straightforward issue for manufacturers to correct.

4.3. Throwing action

The participants who threw with a single, sweeping action (Fig. 8A) had significantly faster deployments than those who employed compound actions (Fig. 8B). Video analysis also demonstrated that, because of the inertia of the deployment bag, it appeared to 'lag behind' the throwing hand during compound actions. This caused a loss of throwing power and appeared to increase the risk of entanglement. In one deployment, it led to the bridle wrapping around the participant's wrist. If that had occurred in flight, it would likely have caused a severe trauma to the upper limb when the reserve opened (Fig. 8C). In another, it led to the participant's face being covered in the lines of the reserve parachute.

While some participants appeared to throw powerfully and with intention, others let the bag drop. The importance of a powerful throw will vary, depending on the situation. In emergencies where the paraglider is falling fast, or with considerable rotational forces, a reserve dropped into the air mass would inflate rapidly. However, in a low-speed but uncontrolled descent, throwing more powerfully might lead to a faster inflation. Based on participants' performance during the study (which had little spatial disorientation, limited acceleration, and only moderate stress), it is unrealistic to hope pilots that would have the presence of mind to throw the parachute in a particular direction (as advised by some schools) or execute a safe compound throwing action during acute severe stress. Therefore, it is felt that a single, backwards, sweeping throwing action should become the standard method to deploy a reserve parachute.

4.4. Participant factors

It was hypothesised that prior experience of reserve deployment would be correlated with improved performance in the study, but that hypothesis was rejected. There were also no strong associations between deployment time and participant age, sex, handedness, self-rated anxiety or currency, flying experience, arm length or angles of flexion when holding the handle.

This might be considered surprising. However, in the opinion of the expert focus groups, even those participants with the most experience of deployment were still very undertrained in the task, likely reflecting the wider paragliding population. They felt that the effects of anxiety, currency or time flying were also likely to pale in comparison to those of undertraining. They were therefore unsurprised at the lack of associations, and viewed it as another argument for strengthening deployment training.

All reserve handles were mounted on the right, unless using a front-mounted system. While handedness affected the behaviour of the non-reserve side hand, it did not affect deployment time, perhaps because grasping the handle did not require precision movement. Arm length and angles of flexion when grasping the reserve handle were also not associated with deployment times, likely because grasping the handle only required moderate, rather than extremes of flexion and therefore did not differ much between pilots.

4.5. Study limitations

While our study represented a major effort to study reserve deployment in a large group of paraglider pilots, it had a number of limitations. The most important was that, unlike in a real emergency, there was no

threat to life. There was no requirement for altitude awareness and also no inhibition to throwing the reserve: in live flight, there is always a judgement required between the need to deploy and the risks of deployment. While our study model was able to provoke some anxiety (which may have improved or impaired performance depending on the participant), participants were always aware that they were safe and were never in doubt that throwing the reserve was the correct decision.

When descending the zipline, participants primarily experienced linear, forward acceleration (Gx forces). However, in many emergencies there are significant and disorientating rotational forces. These would likely have exacerbated many of the difficulties faced by our participants in the study, particularly the 30% of participants who could only locate the handle easily with one hand. Rotational acceleration would also have exaggerated any mechanical disadvantages caused by, for example, long strops or a requirement to laterally extract the deployment bag. Other limitations included a self-selected sample, a practice at handle location before deployment (an opportunity that may not occur in life) and standardisation of gloves and control line grip.

All of the limitations above meant that participants in the study had an easier task than they would face in a real emergency, and many participants still had difficulties deploying their reserve parachute. Therefore, we believe that the findings and recommendations presented in the study are more pressing given the study's limitations, rather than less.

5. Conclusion and recommendations

Real emergency parachute deployments are rare and carry their own hazards. By definition, they happen during emergencies and so are not easily studied prospectively in the field. Equally though, divorcing the action of deployment from its context makes any lessons learned hard to value. This study attempted to characterise reserve parachute deployment in a standardised, yet ecologically valid manner.

This study demonstrated the acute need for improved reserve parachute system design that works in harmony with pilots' natural responses under pressure. 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. It is recommended that:

1. Under-seat systems should position reserve handles on the hip.
2. Handles should be easily encircled by the grip and positioned clear of other harness components.
3. Manufacturers should consider brightly-coloured handles, 'lead lines' or arrows as visual cues to the existence and location of the reserve.
4. Deployment bags be supplied with the harness, strop and handle as part of an integrated system, including an indication of correct orientation during packing.
5. If they are supplied separately, then care should be taken to ensure the strop is of the correct length for the pilot. There is no 'official' guidance for strop length, as with non-integrated systems, it will vary depending on the particular combination of harness and parachute. However, a correctly sized strop would be one long enough to avoid pulling or rotating the deployment bag before the pins are released, but short enough that deployment bag can be pulled well clear of the harness before the pilot's elbow and arm are fully extended.
6. The deployment bag should be extractable at any angle within 90° of the horizontal.
7. Front mounted reserve containers should be secured at the base to prevent them lifting when pulling the reserve handle.
8. Pilots need to increase their reserve deployment drills by an order of magnitude. They should be encouraged to do so as part of a 'post-take off check' and well as multiple times during the flight.
9. Paragliding students need a better understanding of their reserve systems as part of their basic training. This should include reserve

fitting, bridle routing, and the importance of periodically loosening hook-and-loop fasteners. Making in-flight, or zipline deployments mandatory components of training would be impractical. However, 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. This might be difficult to implement as most equipment is bought over the internet. However, it could be an example of best practice.

10. 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.

Future work could include integrating these findings into the wider 'chain of survival', with a particular focus on altitude awareness and cognitive switching, as well as testing reserve handle location and deployment bag extraction during rotational acceleration. The 2018 EN-1651 standard [7] governing paragliding harness design has recently been reviewed. The results of this experiment were presented to the reviewing committee and informed the new standard (EN-1651 + A1:2020 [8]), raising the bar of equipment design to make paragliding a safer form of aviation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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