

# Perception of a Wearable Haptic Feedback Device to Render the Sensation of Flight

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**Abstract**—The FlyJacket is a wearable jacket designed to allow a user to intuitively control a fixed-wing drone by moving their torso. We embedded haptic feedback into the jacket using closed inflated air pouches compressed by motors to provide haptic feedback on the torso. This haptic feedback represents the drone centripetal forces while maintaining the essential lightweight and portable qualities of the jacket. We evaluate this haptic feedback in a user study to test whether it can convey useful haptic information to the user and whether the feedback enhances the user experience of flying. Users were able to understand the direction of the cues without prompting and could distinguish directional cues from the device quickly and with high accuracy. They also described the sensation provided by the device as pleasant. The device was used in a simulated flight task and compared to flying with no haptic feedback. Users indicated that the device increased the realism of the flight, but were split on whether it improved their sense of immersion.

## I. INTRODUCTION

Robots have proven useful for performing tasks where humans are not able to physically reach either due to size constraints or hazardous environments [1]. In these situations, the robot is typically teleoperated so that full autonomy in an unstructured environment is not needed. However, the user frequently lacks information about the state of the robot and the environment because they must rely on only visual feedback [2],[3]. Providing haptic feedback to the user by recreating the forces that the robot encounters while interacting with the environment during a mission has been shown to increase the user’s situational awareness and reduce the number of errors made [4]. Therefore, increasing the realism of the user’s experience of the interaction with the environment is important [5].

Realistic haptic feedback requires not only giving the appropriate type of sensations but also enabling the user to correctly interpret the cues with high accuracy and a rapid response time. Various haptic devices have been developed and demonstrated as effective for providing guidance cues, including pneumatic devices [6], [7], [8], vibrotactile devices [9], [10], and others. However, few of these devices have

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focused on increasing realism and providing improved immersion.

In a previous work [11], we developed a soft upper body exoskeleton to control a fixed-wing drone with intuitive gestures. In [12], we upgraded this exoskeleton by embedding a soft wearable haptic feedback device in order to render the sensations of flying by recreating the forces induced by the centripetal acceleration of a fixed-wing drone. The device, made of closed air pouches that are cable-driven by electrical motors, meets the requirements of being easily embedded into a wearable device, compliant to be safe for the user, and portable to be used in the field during a rescue mission. Since the haptic feedback device is embedded in the jacket, the control and feedback are collocated on the user’s torso to provide a consistent experience of embodiment in the drone. The haptic information transmitted to the user aims at recreating the centripetal forces of the drone, helping the user to perceive the drone changes in attitude and to enhance the immersion of the user in the flight.

In this paper, we investigate the perception of this haptic feedback, the accuracy of the information transmitted to the user, and the impact of this feedback on the realism perceived by the user during the flight.

## II. DEVICE DESCRIPTION

In order to render the aerodynamic sensations experienced by the drone on the user’s skin, we previously developed a novel type of haptic actuator made of a closed air pouch compressed against the body by cables [12]. These actuators aim to produce the sensation of air being compressed against the body to reproduce the drone’s centripetal forces (more description is provided in Section III-C). Four of these closed air pouches were integrated into the FlyJacket: two located in the upper part of the chest and two on the middle part of the back as shown in Fig. 1. The guideline for the design of the jacket was described in [11],[12].

An electrical motor (DC22S, gear ratio 6.6:1, Maxon Motor, Switzerland) mounted on the waist belt pulls on cables (Dyneema 0.4mm, Spiderwire, SC, USA) attached to a rigid plate to compress each pouch. The motors are backdriveable so that they can be controlled to act as bias springs which ensure a minimum cable tension is maintained at all times. The maximum compression force produced by the actuator is 10 N, though the motor voltage could be increased to produce a stronger force. In contrast to vibrotactile actuators, this pouch actuator can provide compressive forces normal to the skin, and since the pouch is compressed by a DC motor,

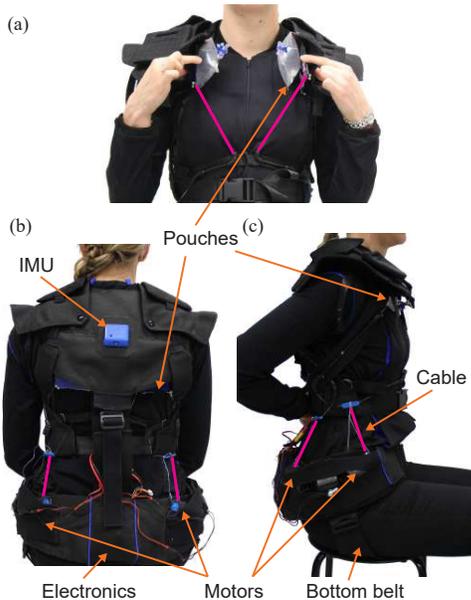


Fig. 1: The FlyJacket with the embedded soft haptic actuators. Cables are highlighted in pink. (a) Front view. The jacket is open to show both front pouches. (b) Back view with the IMU, the electronics, the back motors, and the back pouches highlighted. (c) Side view with the right motors, the front pouch, and the bottom belt highlighted.

it can be lighter weight than a pneumatic actuator with the same range of forces.

To reduce as much as possible the parasitic reaction forces felt at the mounting location of the motors and along the cable routing, padding made of foam was added to the waist belt and the side panels of the jacket. Each motor actuates the pouch located on the same side of the body, so any parasitic forces due to the motors or the cable tension should still be perceived on the same side of the body. The four pouches can be actuated independently and simultaneously. The motor control is performed by an Arduino Mega 2560 (Arduino, Italy) with a shield including two double H-bridge drivers (DRV8412, Texas Instruments, TX, USA) to allow for bidirectional control of the four DC motors. In order to be used in the field, the communication with the computer is wireless using Bluetooth (module RN-42N, Microchip, AZ, USA). These electronic components are located in a pocket on the lower back of the jacket (Fig. 1(b)).

### III. USER STUDY

To test the performance of the haptic feedback, twelve participants took part in the three user experiments described in this section (four women and eight men, age  $27 \pm 4.9$  years; mean  $\pm$  SD). First, the types of sensations perceived by the user were investigated with an open response experiment. Then, the accuracy and reaction time to recognize a directional cue was evaluated. Finally, the performance and sense of realism of the flight was quantified by flying a simulated fixed-wing drone both with and without the haptic feedback. Six of the participants already had experience flying with

the FlyJacket, but none of them had experience with the soft haptic device. During the experiment, they sat on a stool and wore the FlyJacket with the embedded actuators over a single layer of clothing. All participants provided written informed consent prior to the study in accordance with the EPFL Institutional Review Board procedures.

#### A. Open Response Experiment

1) *Methods:* The first part of the user study was a perceptual experiment where the twelve participants were asked to describe the sensations they experienced from the haptic device without wording restriction or suggestion. Four haptic sensations were presented in a pseudo-random order to the participants: the two front pouches, the two back pouches, the two pouches on the right (one on the front and one on the back), and the two pouches on the left. The force of the haptic cues was set at the middle of the possible range of force of the actuator (5 N).

Participants were asked to describe the sensations for each stimulus verbally to the experimenter and to draw on a body map where they felt these sensations. The participants were allowed to experience each stimulus as many times as desired.

2) *Results:* All the participants reported that it was easy to distinguish where on the body the cues were given. The sensations were described as both pulling the torso and compressive forces against the skin on the side corresponding to the cue. Seven participants commented that the sensations were pleasant. Front and back cues were harder to describe due to a larger range of sensations on the torso and because the sensations were sensitive to torso posture (e.g., if the participant bent forward slightly versus kept their torso strictly straight).

When applying the front cue (compressing the two front pouches), nine out of twelve participants described being pulled down and forward. In addition to being pulled forward, three participants reported having the impression of being moved forward. Six participants described feeling compressed. Three of these also reported feeling pulled down and forward.

When triggering the two actuators on the back of the jacket, seven participants described being pulled backwards. Four others related feeling a compression. In addition to other sensations, four participants described that this feedback helped them to straighten their back. Only two participants reported the back cue to feel symmetric to the front cue.

Eleven participants described the sensations for the right and the left cues as symmetric. Half of them (six out of twelve) described a sensation of being pulled down on the side while the other six described it as being bent laterally. In addition to these two sensations, five participants described feeling compressed and five of them described having their shoulder pulled down. Only two of them described sensations on the hip at the waist level (where the motors are located).

3) *Discussion:* All participants correctly recognized the side on which the cues were given and reported force on

TABLE I: CONFUSION TABLE SHOWING ACCURACY FOR FOUR DIRECTIONS

Response	Displayed Direction			
	Front	Back	Right	Left
Front	98.33	0.83	0	0
Back	1.67	98.33	0	0
Right	0	0	100	0
Left	0	0.83	0	100

their body almost exclusively on this side, which indicates that the device has very little parasitic force or reaction force at another location of the jacket. Only a few participants reported feeling a force at the waist level, where the motors are placed. Therefore, padding the waist belt and the cable routing was an effective strategy to localize the sensation. The participants could express the sensations provided by the haptic cues without prompting, and the type of sensation was relatively consistent between the participants, with a clear pattern of compression and pulling force on the corresponding side of the body for all given cues.

### B. Haptic Perception Experiment

1) *Methods:* The twelve participants were asked to identify four directional cues (front, back, right, and left) given by the compression of two of the four air pouches located on their torso. During this experiment, the same type of actuation as for the first experiment was used. The participant could choose when the force started by pressing on a key. The force continued until the participant pressed a key to answer. They entered their response by selecting a labeled key on a computer keyboard. They were asked to use only one finger to perform this task. Participants started with a short training block composed of eight directional cues (two in each direction). They received feedback after identifying each cue, indicating which cue had been displayed and whether they had answered correctly. Then, participants completed an evaluation block of 40 trials where no feedback on the correctness of their answer was given. The evaluation was composed of ten instances of each directional cue. Each participant received unique pseudo-random training and evaluation blocks. At the end of the task, they were asked verbally if one directional cue was easier to recognize than the others.

2) *Results for Accuracy:* Table I shows the results for accuracy. Participants were almost always able to identify the directional cues. Over 480 total evaluation trials, participants correctly identified direction cues with an accuracy of 99.2 percent. All of the errors except one were between the front and the back of the torso. The four errors (over the 480 trials) were made by three participants (P3, P8 and P9). Participant (P9) made two errors. He reported to be confused between the front and the back cues and could not identify them correctly at the end of the training period.

3) *Results for Identification Time:* Fig. 2 shows the response time for each directional cue. The mean time to respond for the front (0.83 s) and the back (0.83 s) are

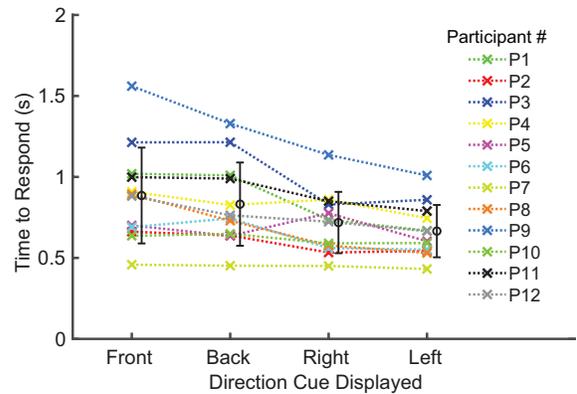


Fig. 2: Time to respond for the four direction cues displayed to the participants. Crosses (×) show the mean time to respond for each participant. Circles (o) display the group mean and the error bars the standard deviations.

slightly higher than for the right (0.72 s) and left (0.67 s). Also, the standard deviation is larger for the front (0.30 s) and the back (0.26 s) than the right (0.19 s) or the left (0.16). However, there is only a statistically significant difference (based on a Wilcoxon rank test) between the time to respond for the front and the left cues ( $p = 0.0351$ ). There are no statistical differences between the other directional cues.

After the experiment, nine participants (out of twelve) reported that the right and left directional cues were easier to recognize than the front and back cues. Among these nine participants, four of them added that the front and back cues were still easy to recognize. Two other participants found all the cues equally easy to recognize (P7 and P11). Finally, participant (P5) found the back cue easiest to recognize, which correlates with her lower time to respond for this direction. These post-experimental subjective reports correspond to the higher average and standard deviation time to respond for the front and back cues recorded during the experiment.

The time to respond shows more variance between individuals than across the different directional cues for a single individual. Participant (P9), who made the highest number of mistakes, had the highest time to respond for all cues while participant (P7) had the fastest time to respond for all cues.

4) *Discussion:* The low number of errors in identifying the direction of the cues demonstrates that the haptic devices embedded into the FlyJacket were able to clearly display directional information. Although all the directional cues were easily identifiable, right and left cues were slightly easier to discern than the front and back cues, and it also took slightly less time to identify them. This is consistent with the impression of the participants. The speed at which the haptic cue is understood by the user is a critical aspect of the device's performance. The mean response times, also including the hand displacement between keyboard keys, for all the cues are lower than one second. This time to respond is meaningfully faster than comparable tests done for pneumatic haptic devices [6], [7] or vibrotactile device [9].

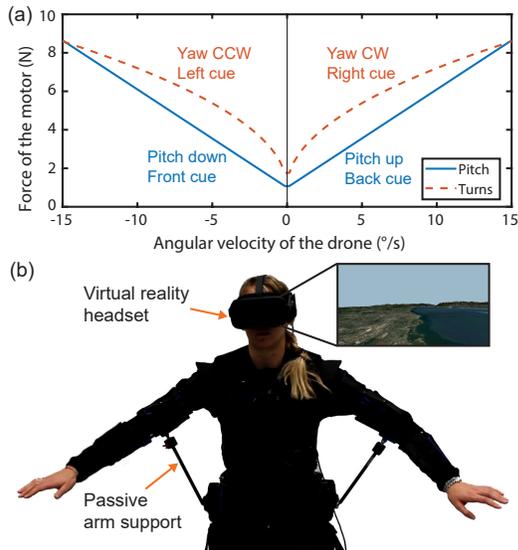


Fig. 3: Flight experiment. (a) Relation between the angular velocities of the drone and the force of the motors for the pitch angular velocity (blue solid line) and the yaw angular velocity (orange dashed line). (b) Setup for flight with inset showing the virtual environment.

The high accuracy and short time to respond make this device efficient and intuitive to transmit directional information to the user.

### C. Simulated Flight Experiment

1) *Methods*: The haptic feedback was used to render the centripetal forces of the drone, making the user aware of the drone rotation and its inertia. Therefore, the twelve participants felt forces on their torso corresponding to their maneuvers only during drone rotation (i.e. if the drone is going straight, no force is rendered). To make the information the user receives straightforward, the aerodynamic forces of the drone (drag, lift, etc.) were not recreated; rather, the angular velocities of the drone are converted to compressive forces on the torso. The pitch angular velocity is translated to front and back cues while the yaw angular velocity is translated to the left and right cues (i.e. during turns). Additive combinations of pitch and yaw cues are possible because the four motors can be independently actuated.

The relationship between angular velocity and the force rendered during the flight was given by the curve shown in Fig. 3(a). Preliminary flight tests showed that the force feedback was hard to detect for small turns to the side (the yaw direction). Therefore, the force profile of the actuators for the yaw movements is based on the square root of the angular velocity, in contrast to the linear curve used for the front and back cues. This quadratic curve aims to give more noticeable change in force for small changes in angle while remaining within the maximum force capabilities of the device.

To avoid slack in the cables, the motors are controlled to act as a bias spring. A force of 1 N is always applied to the

cables (which corresponds to the offset in the graph of Fig. 3(a)). When the user bends toward one of the motors, the motor winds the cable onto the motor pulley. Since this bias force is very small and the motor is backdriveable, the user is still easily able to move (and thereby unwind the cable from the pulley).

Participants were in the same setup as for the two previous experiments, with the addition of the virtual reality headset (Oculus Rift, Facebook, CA, USA), which provided the visual feedback of the simulated environment and the sound of the wind (Fig. 3(b)). Their torso movements were recorded with an IMU (Xsens, Enschede, The Netherlands) placed on the middle of the back (Fig. 1(b)), and they wore passive arm supports to prevent fatigue, as in our prior work [11].

During this experiment, participants performed two one-minute free flights in the simulated environment, once with the haptic feedback and once without the feedback. Then, they performed two more flights (one with feedback and one without) which consisted of following 34 waypoints in the sky symbolized by white clouds forming a trajectory. The waypoints were spaced approximately 30 meters apart from each other. This task is similar to that in [11]. The goal of this second task was to force participants to perform each of the flight maneuvers (pitch up, pitch down, turn left, and turn right) eight times (randomly ordered) with two additional waypoints at the beginning and the end of the trajectory. While the primary purpose of this task was to measure the realism of the flight and the haptic feedback, task performance was also evaluated by recording the distance from the drone trajectory to the center of each waypoint and computing the Root Mean Square (RMS) error for all the waypoints. For both tasks (free flight and the waypoint following) half of the participants (P1, P2, P6, P8, P10, P12) flew with haptic feedback first, while the other half first flew without haptic feedback to account for learning effects and potential bias based on the order of presentation.

After each waypoint following task, participants filled out a questionnaire regarding the sensations they experienced during the flight. Using a Likert scale from 1 to 7 (1 being “Not at all” and 7 “Very much”), the participants rated their appreciation of the flight for both conditions (i.e. with and without feedback) on a variety of criteria. Questions are displayed in Table II. Four themes — realism (Q1 and Q2), immersion (Q3 to Q5), performance (Q6 to Q9), and force perception (Q10 and Q11) — were assessed. For Q1 to Q9, the relative performance (the difference in rating) between the flights with and without feedback was calculated. A positive value means that the haptic feedback improved the perception. Q10 and Q11, which concerned only the experience of feeling the haptic feedback during the flight, were asked only after the task with feedback. The statistical significance of the groups were evaluated with a one-sample t-test.

2) *Results*: The haptic feedback had on average no influence on the flight performance with a relative improvement of performance of  $3.7 \pm 12.3$  meters; mean  $\pm$  SD. The order of flight conditions appears to have more effect than

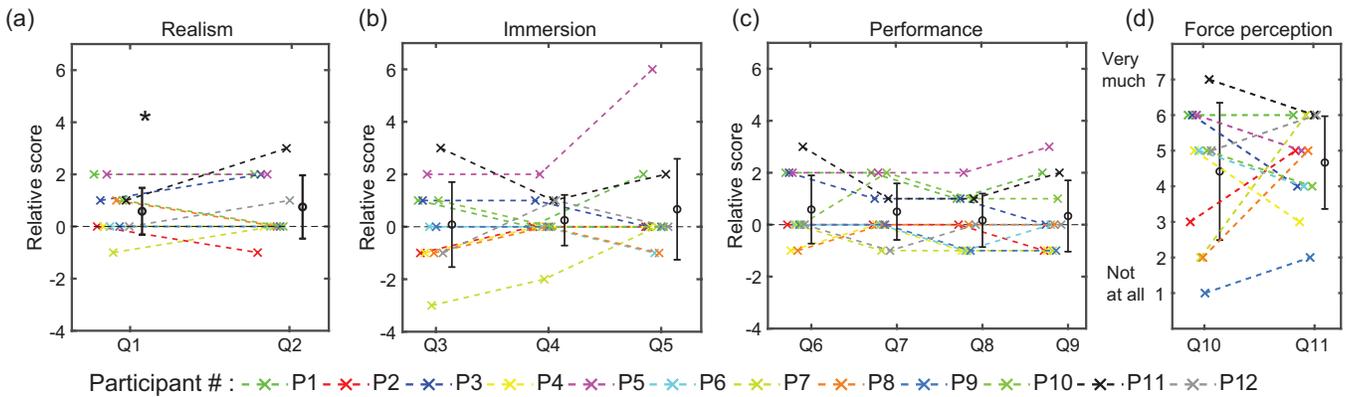


Fig. 4: Results of the questionnaire. Crosses (×) show the mean time to respond for each participant. Circles (o) display the group mean and the error bars the standard deviations. Responses to questions concerning: (a) the realism of the flight. Asterisks (\*) denotes  $p < 0.05$ , (b) the immersion into the flight, (c) the participant’s subjective perception of their performance, and (d) the force perception.

TABLE II: LIST OF QUESTIONS PRESENTED TO THE PARTICIPANTS

	Index	Questions
Realism	Q1	I felt as if I was flying.
	Q2	How realistic was the flight?
Immersion	Q3	How well do the sensations match your expectation?
	Q4	How immersive was the flight?
	Q5	I enjoyed the experience of virtual flying.
Performance	Q6	How intuitive was the flight?
	Q7	How confident performing the flight were you?
	Q8	How easy was the task?
	Q9	How well were you able to control the flight?
Perception	Q10	The haptic feedback improved my flight performance.
	Q11	How much did you feel the haptic feedback during the flight?

the haptic feedback, because ten participants performed better during their second task regardless of the feedback condition. The performance of one participant (P6) was much better with the haptic feedback even though she started with this condition. She reported feeling disoriented and having motion sickness during the flight without the feedback.

Results from the questionnaire are shown in Fig. 4. All the participants except participant (P9) (who had trouble recognizing the directional cues in the previous experiment) thought that the haptic feedback improved their performance (Q10) with eight of the participants rating this question with a score of five (out of seven) or higher. The amplitude of the force feedback (Q11) was sufficient according to the participants as ten of them rated a score of four or more and only two participants reported post-experiment that they would like to have a stronger force.

The relative ratings for the questions regarding the performance (Q6-9) is quite diverse. Participants with generally negative relative scores reported that the haptic feedback “reduced their reactivity” (P7), “prevented them from doing what they wanted” (P12), or “had too much time delay” (P8).

On the other hand, participants who gave the haptic feedback an overall positive rating reported that they were more aware of their position and their movements when flying (P1, P3, P6, P10, P11, P12) or felt more stable (P5).

Participants rated the flight more realistic with the haptic feedback with Q1 significantly different from zero ( $p = 0.0463$ ) and Q2 almost significantly different from zero ( $p = 0.058$ ). Mostly, participants described the flight with feedback as being more natural, more comfortable, and less weird than without the feedback. On the other hand, the results for the immersion are more disparate. For half of the participants, the sensations given by the haptic device did not match their expectations, and they reported that they expected to feel sensations on the whole body to feel totally immersed. The same participants who rated negatively for this set of questions also rated negatively for the questions about performance.

3) *Discussion*: From the results of Fig. 3, two clusters of user perception of the haptic feedback can be seen; half of the participants were very optimistic about the feedback and had a good acceptance of it while the other half were more skeptical of the feedback, rating the flight experience with feedback either the same or one grade lower than the flight without feedback. The main comments of the skeptic group were that the haptic feedback prevented them from moving and reduced their reactivity. This is a reasonable response given that the haptic feedback was designed to render the centripetal forces and therefore the inertia of the drone. These participants were not convinced by the rendered sensations. On the other hand, half of the participants found that the haptic feedback improved the realism of the flight, their immersion in the flight control task, and their performance of the task. With regard to the disparate views on whether the sensation matches the user’s expectation, it should be noted that people are generally not familiar with the actual sensation of flying, and the users had widely variable expectations. Participant (P3) has extensive experience remotely piloting an aircraft (~500 hours), one other participant (P12) has 10

hours of experience, and all other participants have at most 2 hours of experience. P3's rating for all questions was positive except for Q5 and Q9, which were rated the same for with and without haptic feedback. He reported that having the inertia of the flight rendered made the flight more realistic.

Half of the participants reported that the flight was more realistic with the addition of the haptic feedback. Three participants (P5, P6 and P11) reported feeling less motion sickness when flying with the haptic feedback, and none of the participants reported feeling motion sickness during the flight with feedback.

#### IV. CONCLUSION

In this paper, we presented a user study to evaluate the effectiveness of a soft haptic feedback device that is embedded in the FlyJacket and provides haptic feedback to the torso. The device was able to transmit directional cues to the user with very high accuracy, and the response time is meaningfully lower than for comparable devices. These features show that this device could be used for guidance, which could be tested with the same type of experiment as performed in [13]. This device has the advantage to be more compact than the one presented in this previous work.

When applying this feedback during a simulated flight, the realism of the flight increases significantly, but the performance of flight did not improve. The perception of immersion was less consistent between the users with half of the participants enthusiastic about the feedback while the other half was more skeptical. Some participants disliked the impression of having an inertia while flying, which is the sensation recreated by the device, because it prevented them from moving while other participants emphasized that this same sensation of inertia made the flight more immersive and realistic.

The realism of the sensation provided by the device could be further improved by consulting experts in free fall and wingsuits in order to compare these sensations with what would be the closest to reality. Since the actual sensation of flying has been experienced by very few people, the expectation of the sensation varied widely among participants.

Modifications to the hardware could be done in order to improve the user's immersion in the flight. The size, number, and location of the pouches is not limited to the current configuration, so different arrangements and combinations may provide a better experience. Pouch actuators could also be added on the arms to increase the surface receiving the haptic feedback. However, adding more pouches increases the jacket complexity and weight. The reactivity of the feedback could be increased by changing the command of the motors to make the force profile more aggressive and reducing the time delay between the motor actuation and the point at which the sensation is detected on the skin.

Since the users are already receiving good visual feedback of the flight, it is not surprising that the performance did not improve. The device could be further tested in situations with increased visual or cognitive load. An interesting fact that was observed during the experiment is the report of some

participants of having less motion sickness when flying with the haptic feedback. These results warrant further study and quantification, as motion sickness is a well-known problem when performing virtual reality tasks [14].

Some differences in perception may appear between the two static experiments and the dynamic flight experiment. Additional future experiments could provide a deeper understanding of these differences and their influence on perception.

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